

DARK MATTER

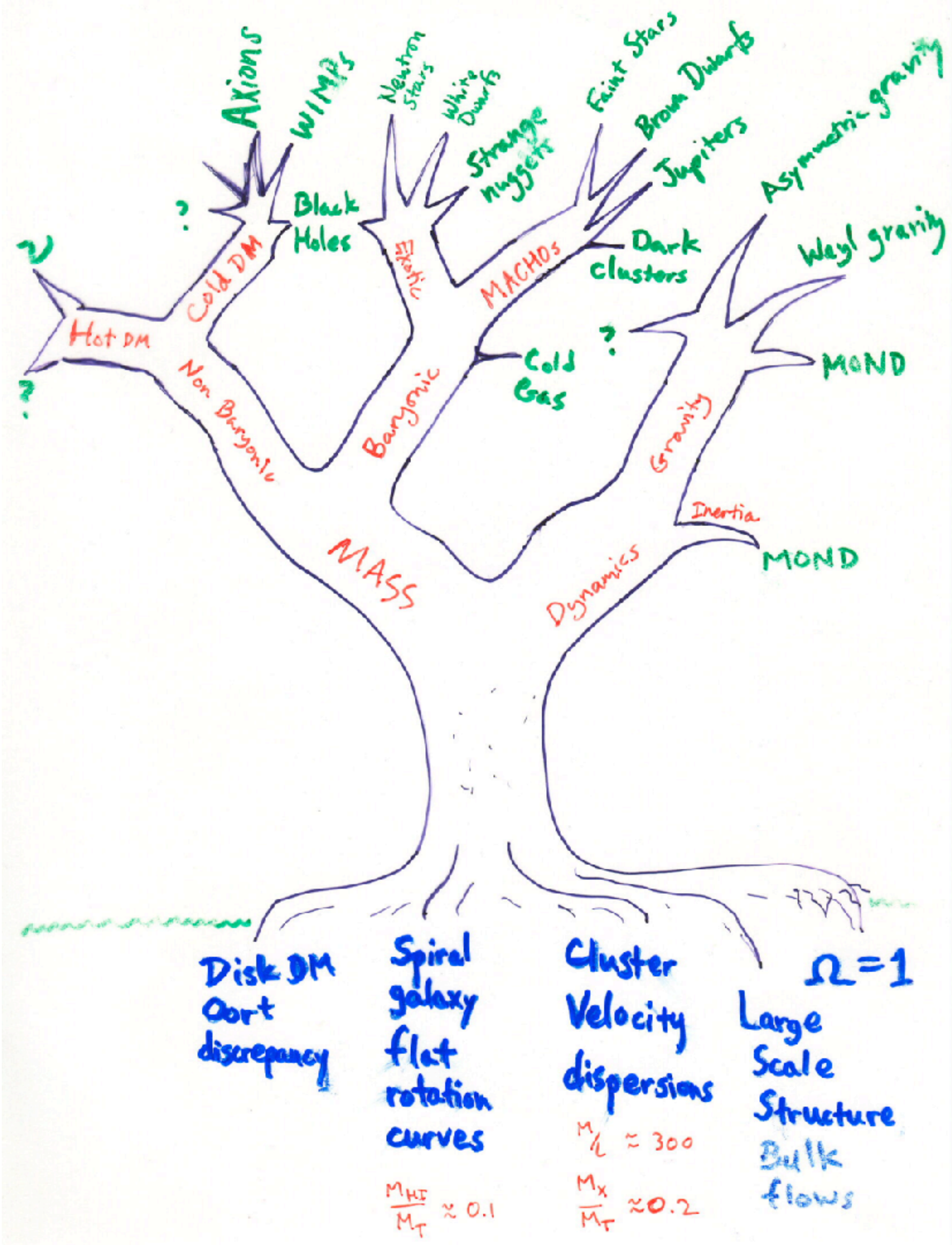
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SEARS 552

<http://astroweb.case.edu/ssm/ASTR333/>

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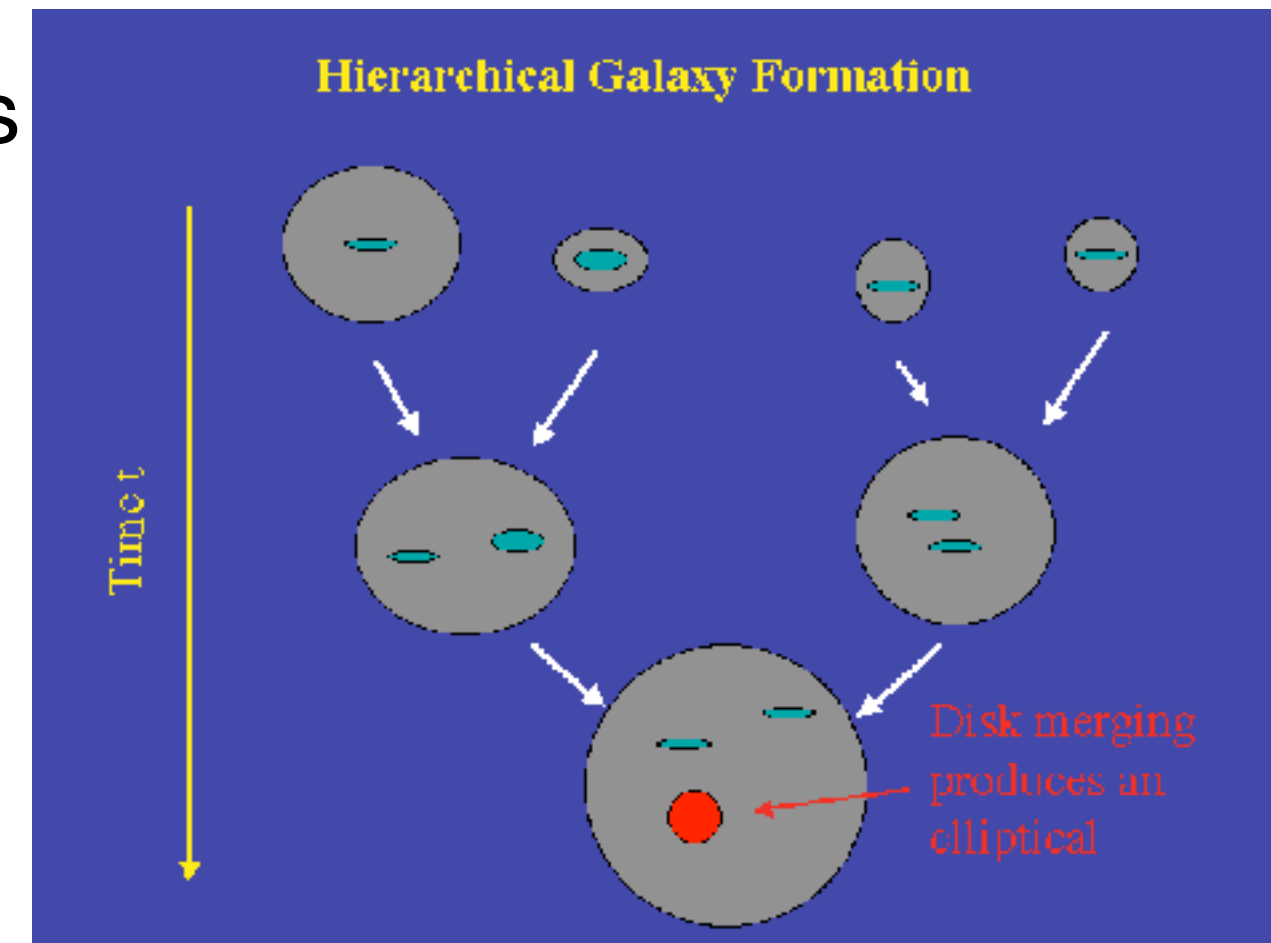
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Homework DUE next time
Midterm March 5



Galaxy formation with Cold Dark Matter

- CDM first, then baryons** **hierarchical**
1. **Dark matter halos form; merge** into ever larger masses
 2. **Baryons fall in** to the potential wells of DM halos
 3. **Gas cools, sinks** to centers of DM halos
 - Halos compressed by sinking baryons
 - gas forms rotating disks at centers of DM halos
 4. **Stars form** in disks
 - *Feedback* heats gas, dissuading further gas accretion
invoked to fix various problems
 5. Mergers transform some disks into ellipticals
 - star formation truncated
 6. Renewed gas accretion may re-form disks around ellipticals
 - thus becoming the bulges of S0s and early type spirals
 7. Merging lessens; more gradual accretion of dark matter and gas may continue
 8. **Galaxies**



merging fundamental to hierarchical galaxy formation, but this doesn't have to be the only way to make elliptical galaxies



Fundamental elements in **bold**; other details subject to revision.
“*Feedback / baryonic physics*” is an auxiliary hypothesis invoked to save the phenomena

Generic CDM problems

- Fine-tuning
 - Laws of galactic rotation do not follow naturally from CDM
 - Too little scatter in TF, RAR - galaxies look like MOND
- Too much mass at small radii
 - Cusp-core problem (esp. in dwarfs)
 - Massive bulges too common
- Missing Satellites / Satellite Planes / Too Big to Fail
 - too few satellites around bright galaxies
 - phase space wrong
 - mass function problem in the field (not just satellites)
 - overcooling/condensation problem

Generic prescription: Feedback

Gas cools, sinks to centers of DM halos - gotta happen, but how?

Condensation

Gas falling into a DM halo shock heats to the virial temperature

$$T_{vir} = \frac{2}{3} \frac{GM_{vir}}{R_{vir}} \frac{\mu m_H}{k_B}$$

In absence of cooling, supported in hydrostatic equilibrium

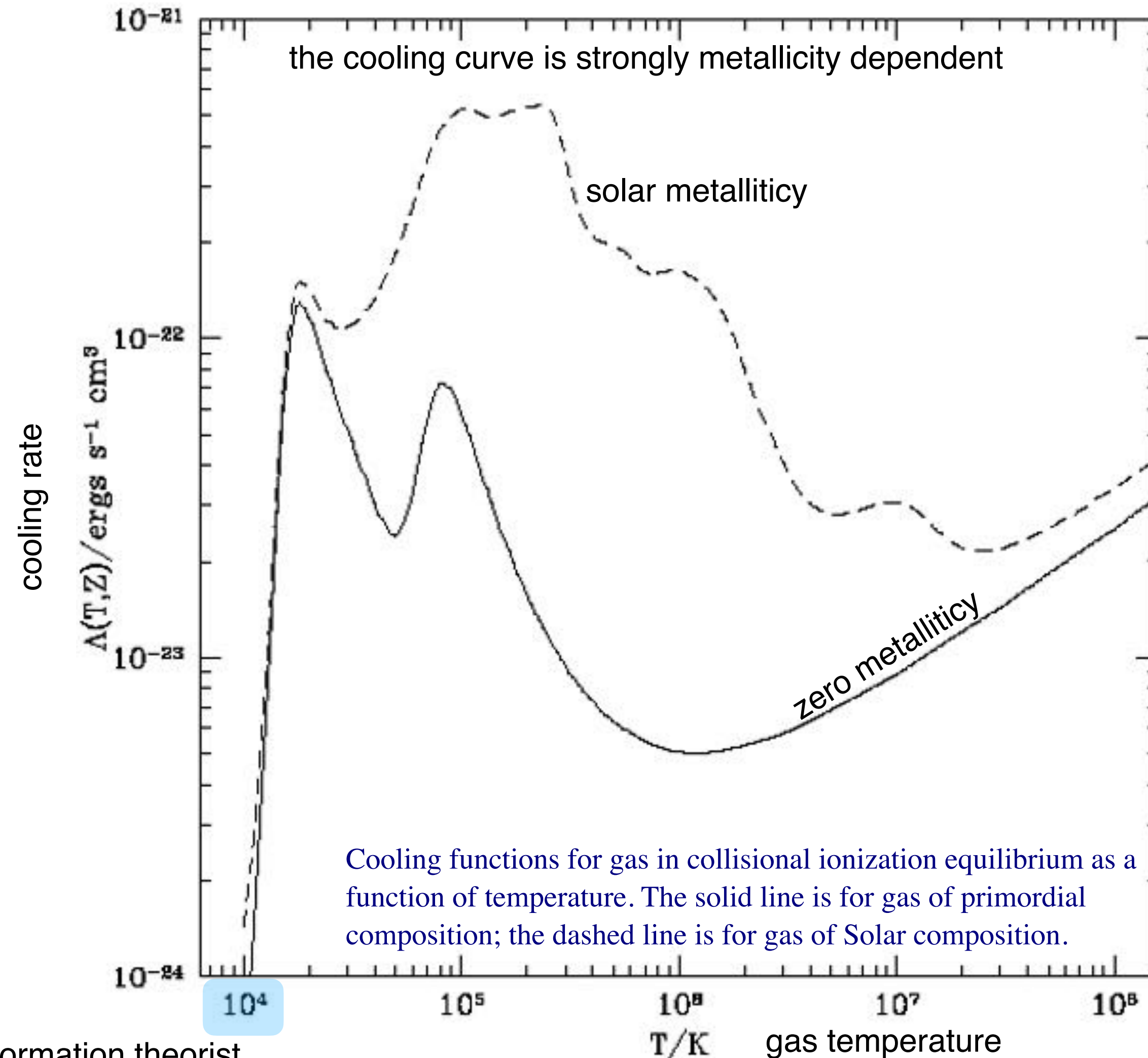
$$\frac{dP}{dr} = - \frac{GM(r)}{r^2} \rho(r)$$

Gas cools inside out at a rate that depends on density and metallicity

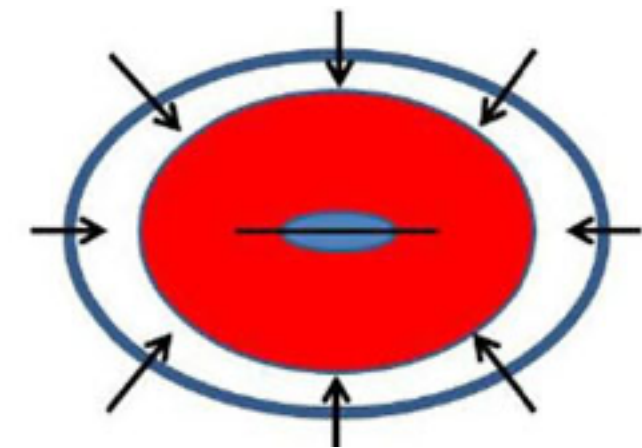
$$\mathcal{L} = n_H^2 \Lambda(T, Z)$$

Even a small amount of heavy elements provide a lot of emission lines that enhance the cooling rate.

Any $T < 10^4$ K is "cold" to a galaxy formation theorist.

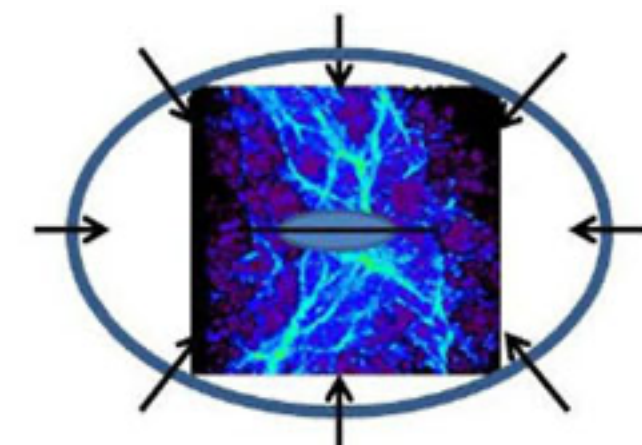


Gas falling into a DM halo shock heats to the virial temperature



Gas cools inside out; innermost baryons form gas disk

Or maybe gas arrives in cooling flows along cosmic filaments



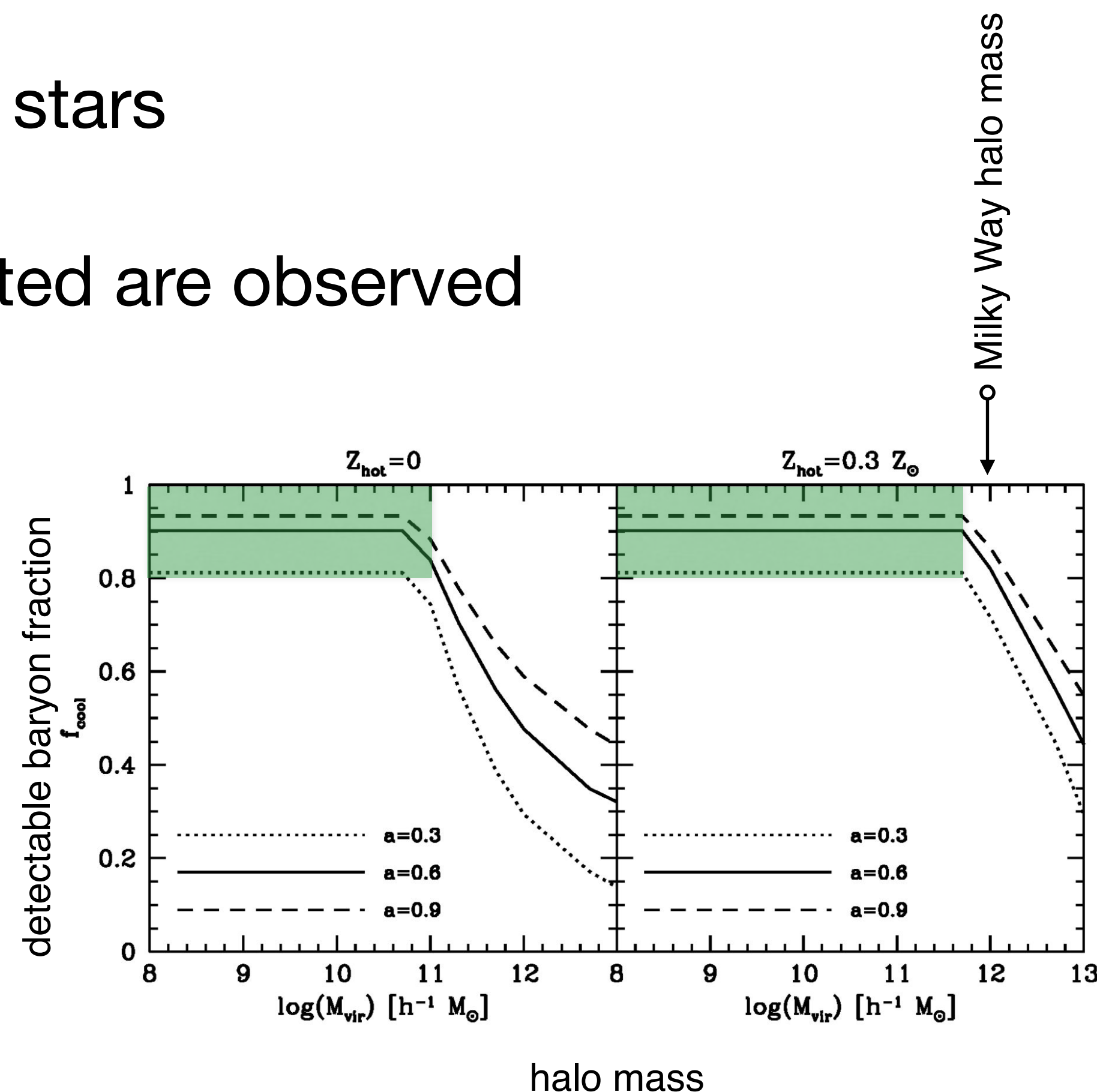
Shlosman (arXiv:1212.1463)

Condensation problem

- Baryons in low (galaxy) mass halos have time to cool
 - Should condense & form stars
- Fewer baryons than expected are observed

The fraction, f_{cool} , of baryonic mass inside the virial radius that has cooled and settled in present-day discs as function of the present-day virial mass. (van den Bosch 2001)

Nearly all baryons in galaxies have time to cool; should result in the baryon fraction on each halo being close to the cosmic baryon fraction (16%) and the galaxy luminosity function paralleling the halo mass function.

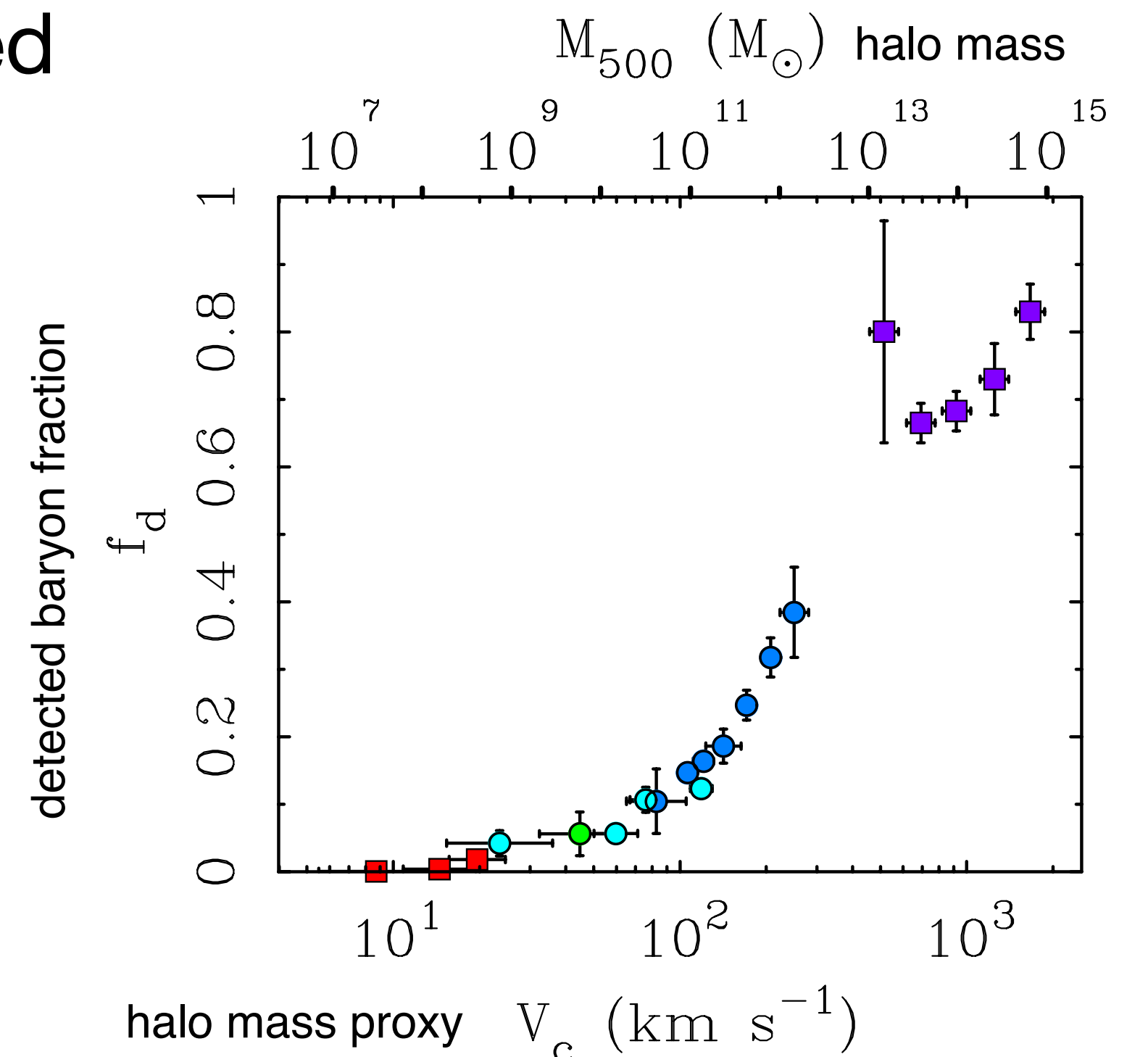


Condensation problem

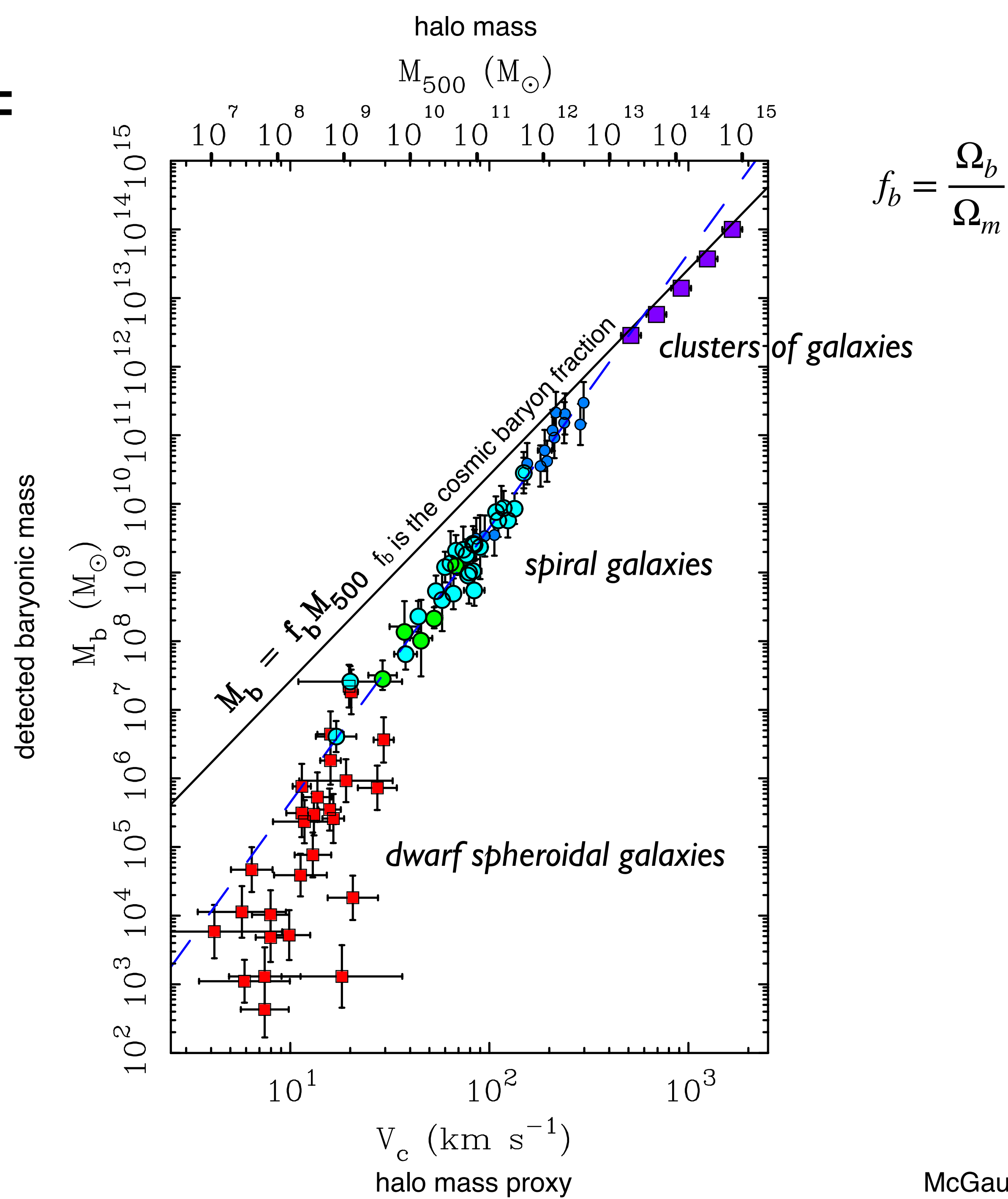
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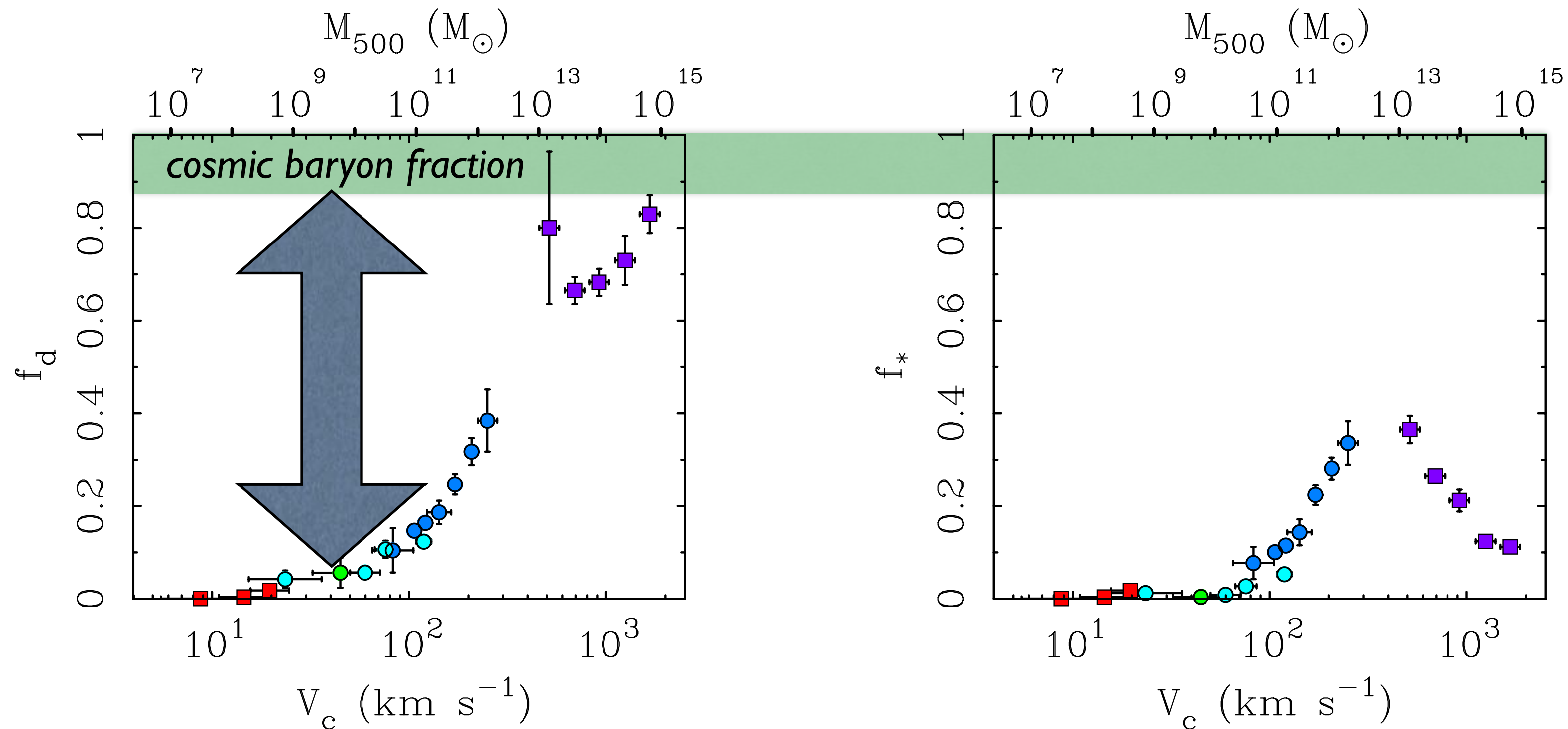
Extended TF



$$f_d = \frac{M_b}{f_b M_{500}}$$

$$f_* = \frac{M_*}{f_b M_{500}}$$

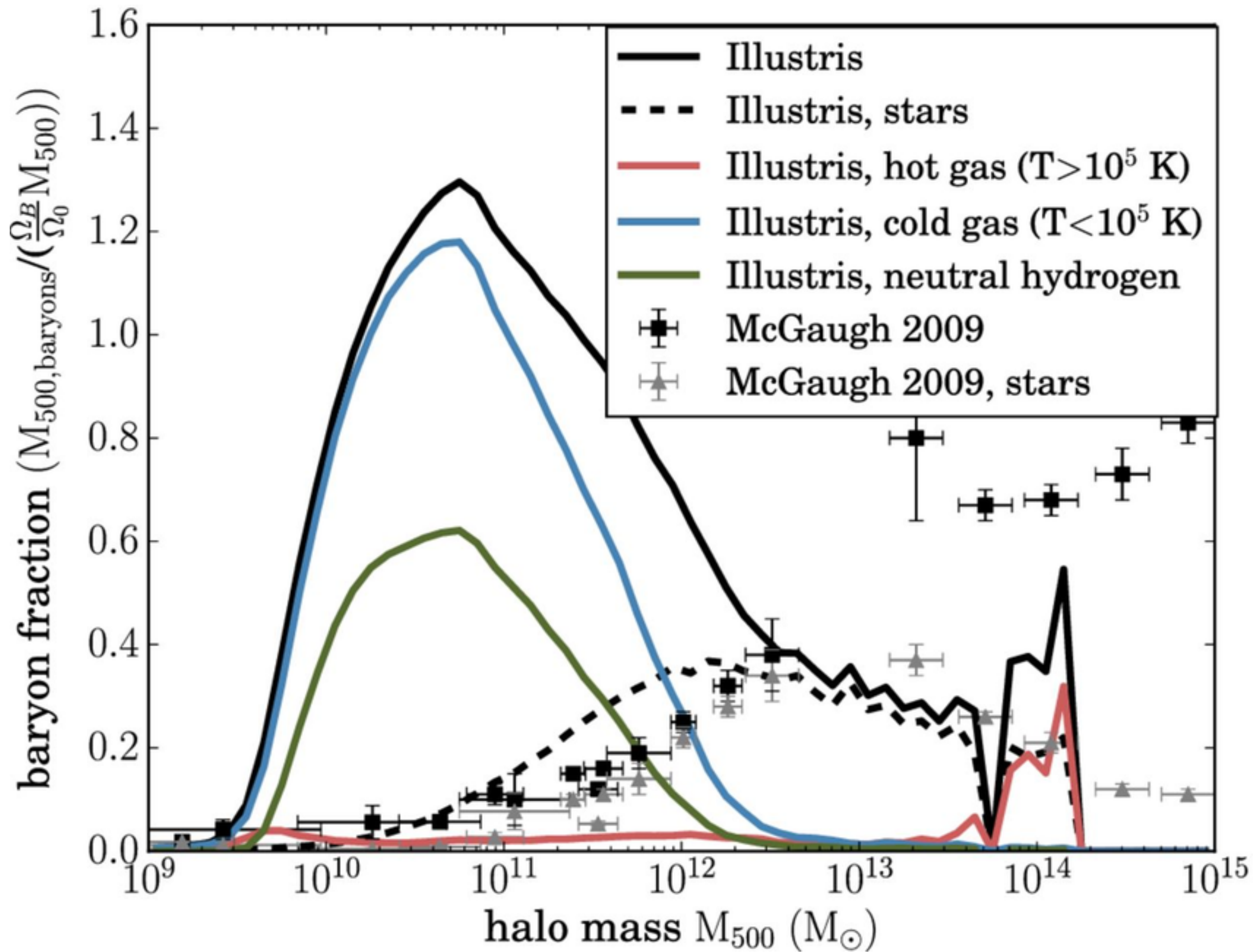
$$f_b = \frac{\Omega_b}{\Omega_m}$$



McGaugh et al. (2010)

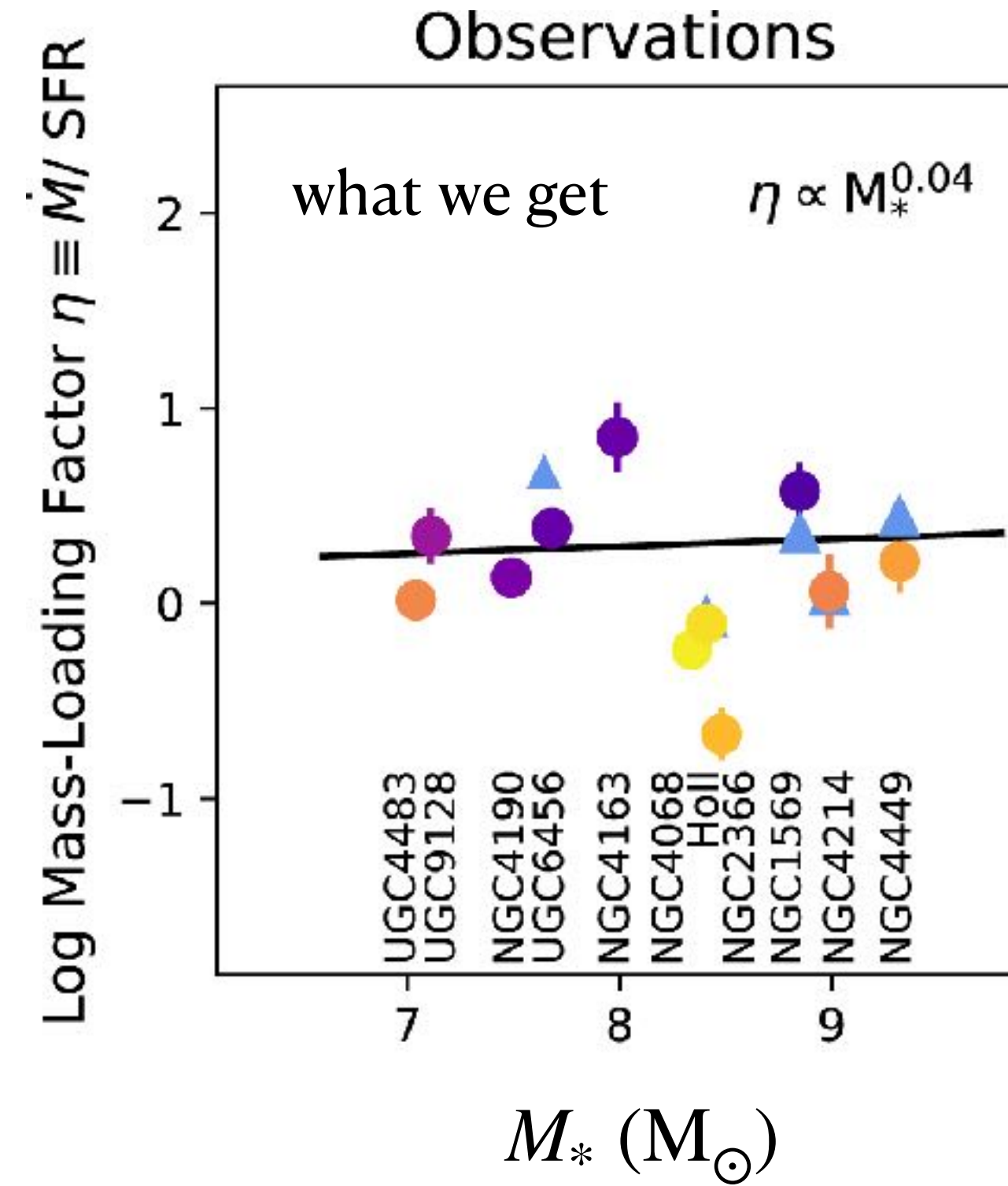
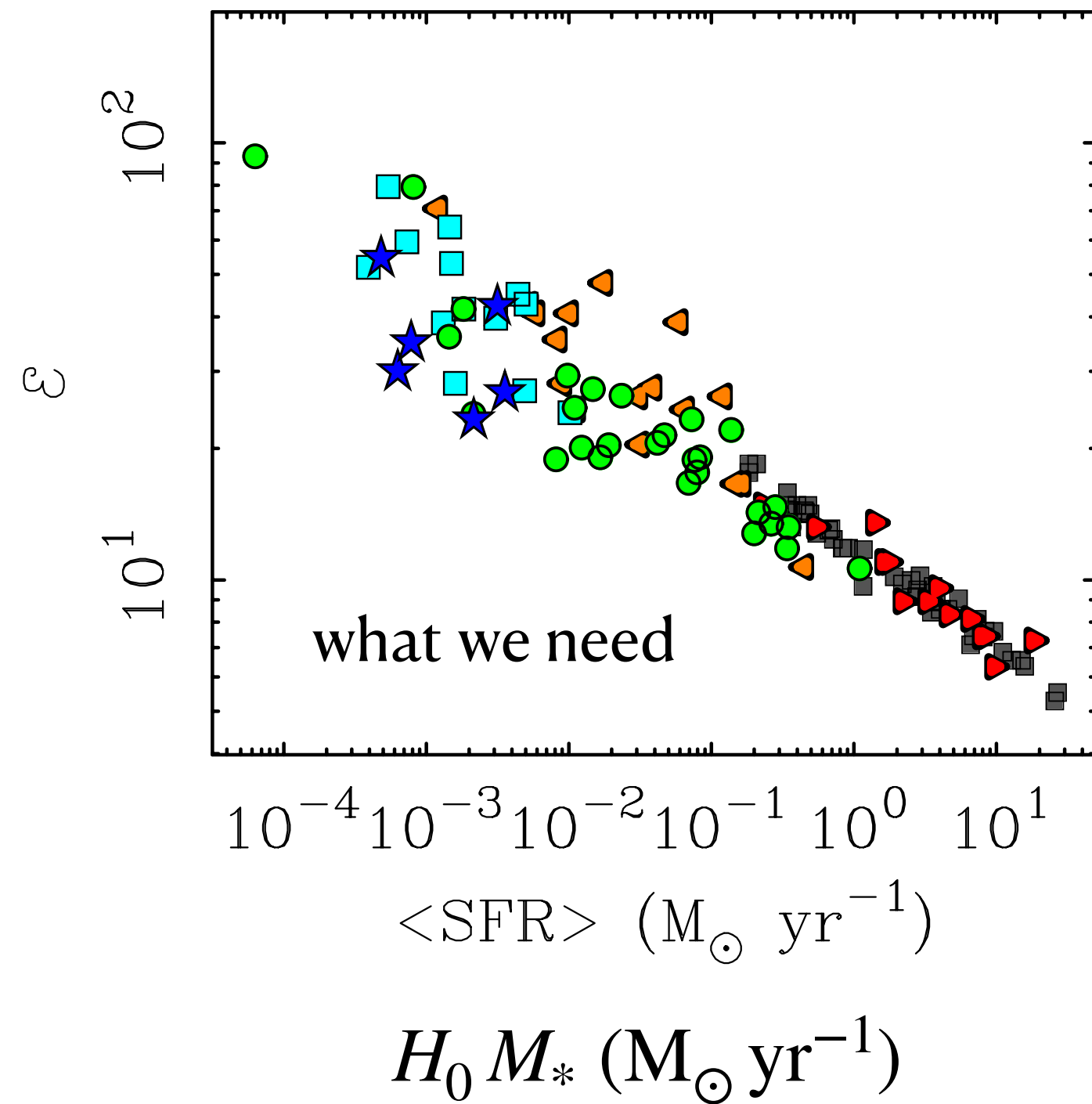
Halo by halo missing baryon problem

2 missing mass problems: baryonic AND non-baryonic DM



Feedback

invoked to explain cusp-core problem and missing baryon/missing satellite problem



Efficacy of feedback: $\log \epsilon = 3 \log f_V - \log f_d$.

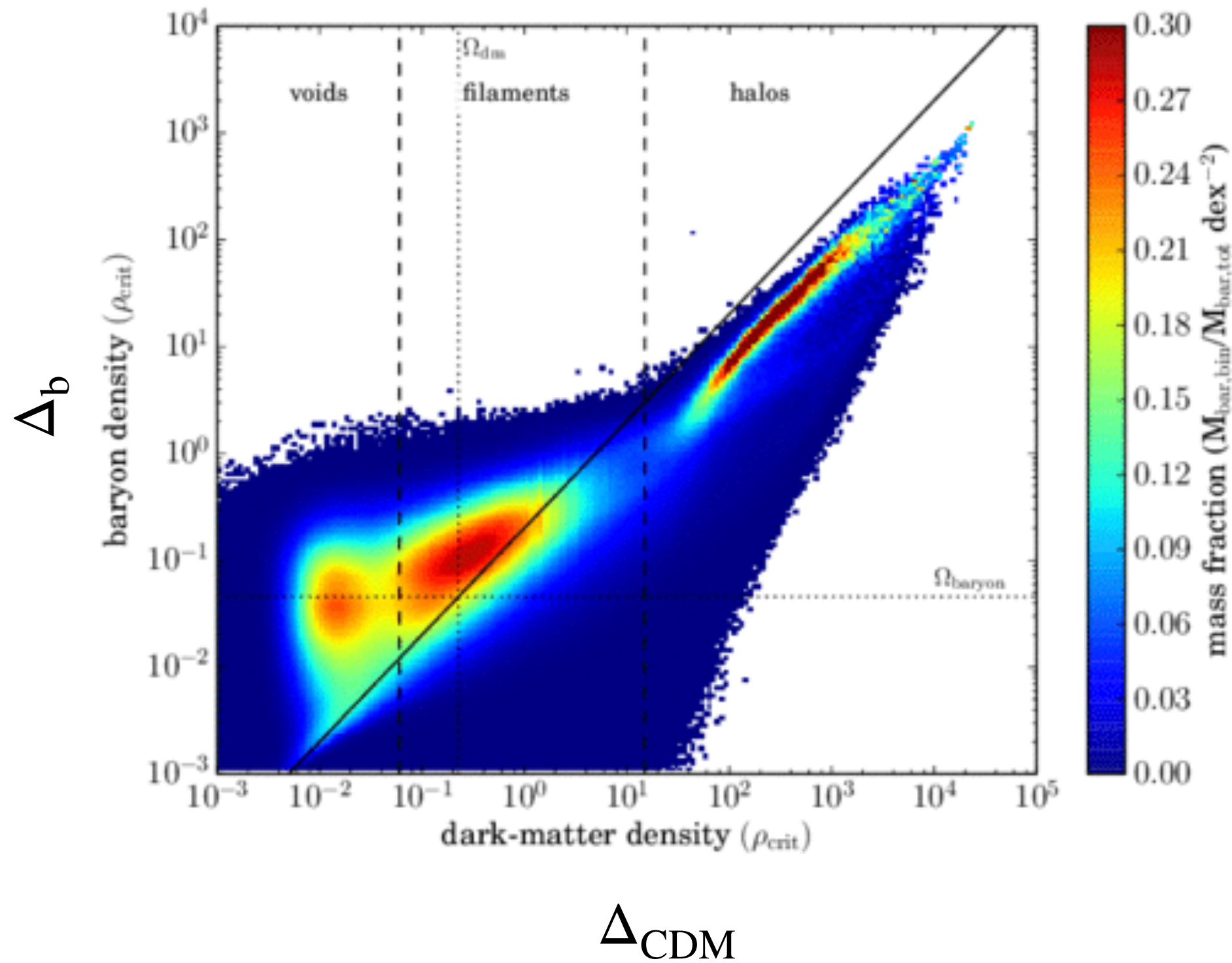
Basically the ratio of baryons lost to those retained.

Most baryons are missing, especially from low mass halos.

$$f_d = \frac{M_b}{f_b M_{500}}$$

$$f_v = \frac{V_f}{V_{500}}$$

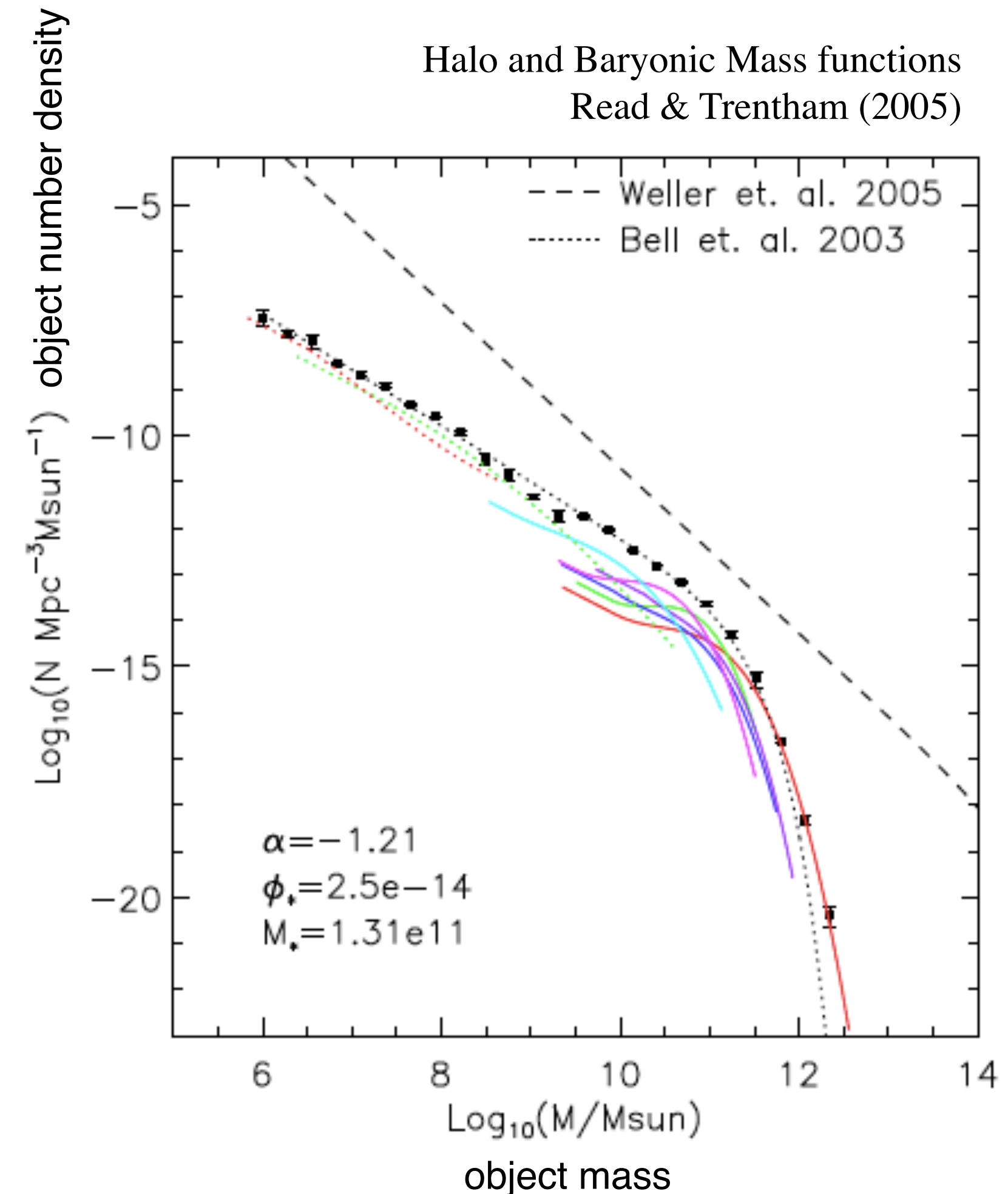
component	dark matter density region (ρ_{crit})	% of total dark matter mass	% of total baryonic mass	% of total mass	% of total volume
haloes	> 15	49.2 %	23.2 %	44.9 %	0.16 %
filaments	0.06 - 15	44.5 %	46.4 %	44.8 %	21.6 %
voids	0 - 0.06	6.4 %	30.4 %	10.4 %	78.2 %
ejected material inside voids	0 - 0.06	2.6 %	23.6 %	6.1 %	30.4 %



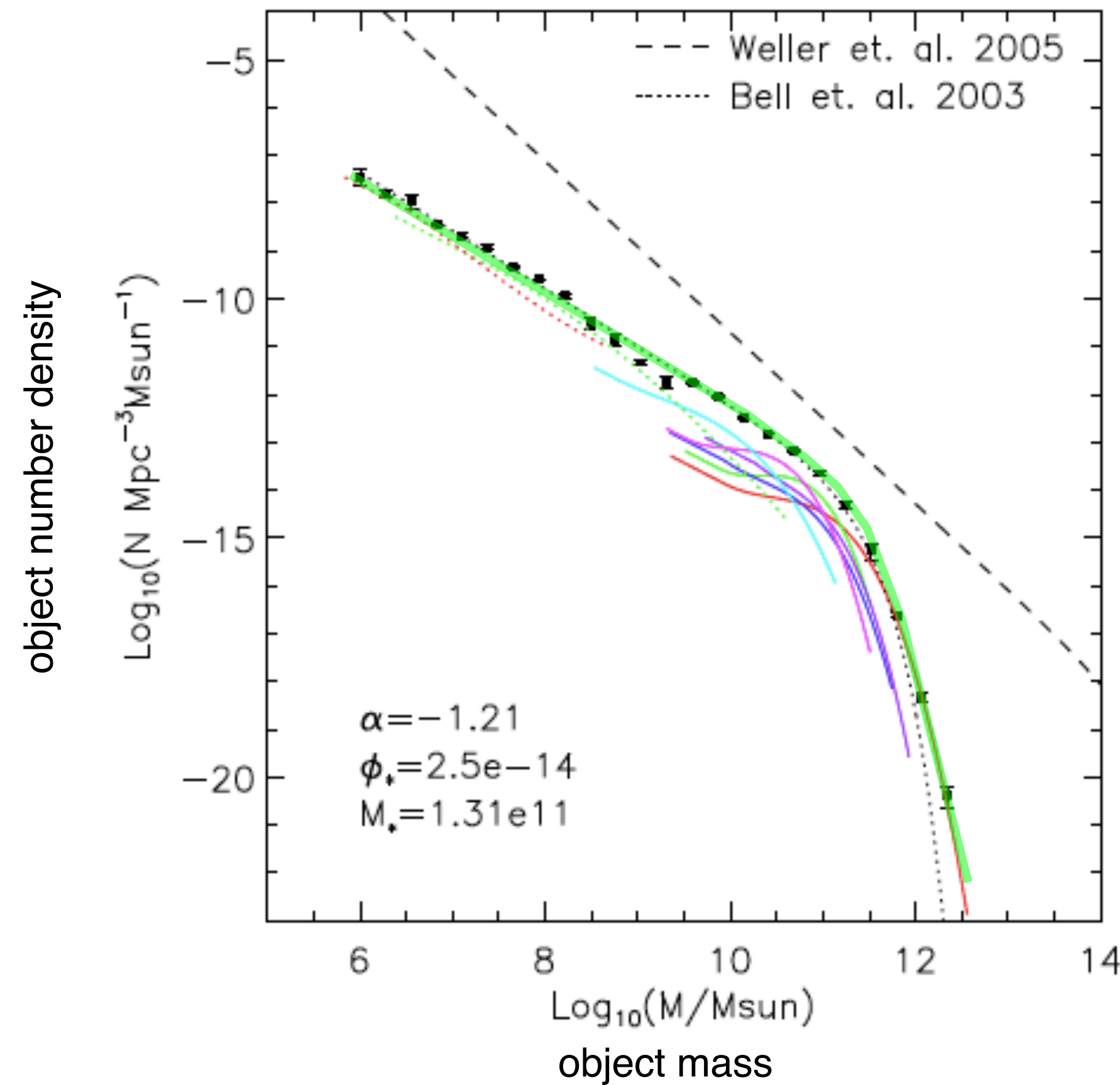
ature and metallicity maps with Fig. 3 and that the majority of the baryons in voids is warm to hot gas enriched by metals. Those most likely been ejected from the haloes through. Because the ejected material has a higher temperature than the other baryons in voids, we can use the temperature to discriminate between baryons naturally residing in voids and baryons which have been transported there. We define an additional ‘ejected material’ region in Table 2 with a temperature higher than 6×10^4 K to the dark matter density cut. With 23.6% of the total baryons, this ‘ejected material’ region is responsible for about 40% of the baryons in dark matter voids. In Fig. 3, the region corresponding to the ejected material is shown in red, indicating that it fills about 40% of the voids. We should note that the ejected mass most likely heats some of the gas already present in the voids. Therefore, we

Condensation problem

- Galaxy luminosity function should descend from the halo mass function
- predicted: steep power law
- observed: Schechter fcn with shallow faint end slope
- Fewer galaxies than expected are observed



Baryonic Mass Function (Read & Trentham 2005)

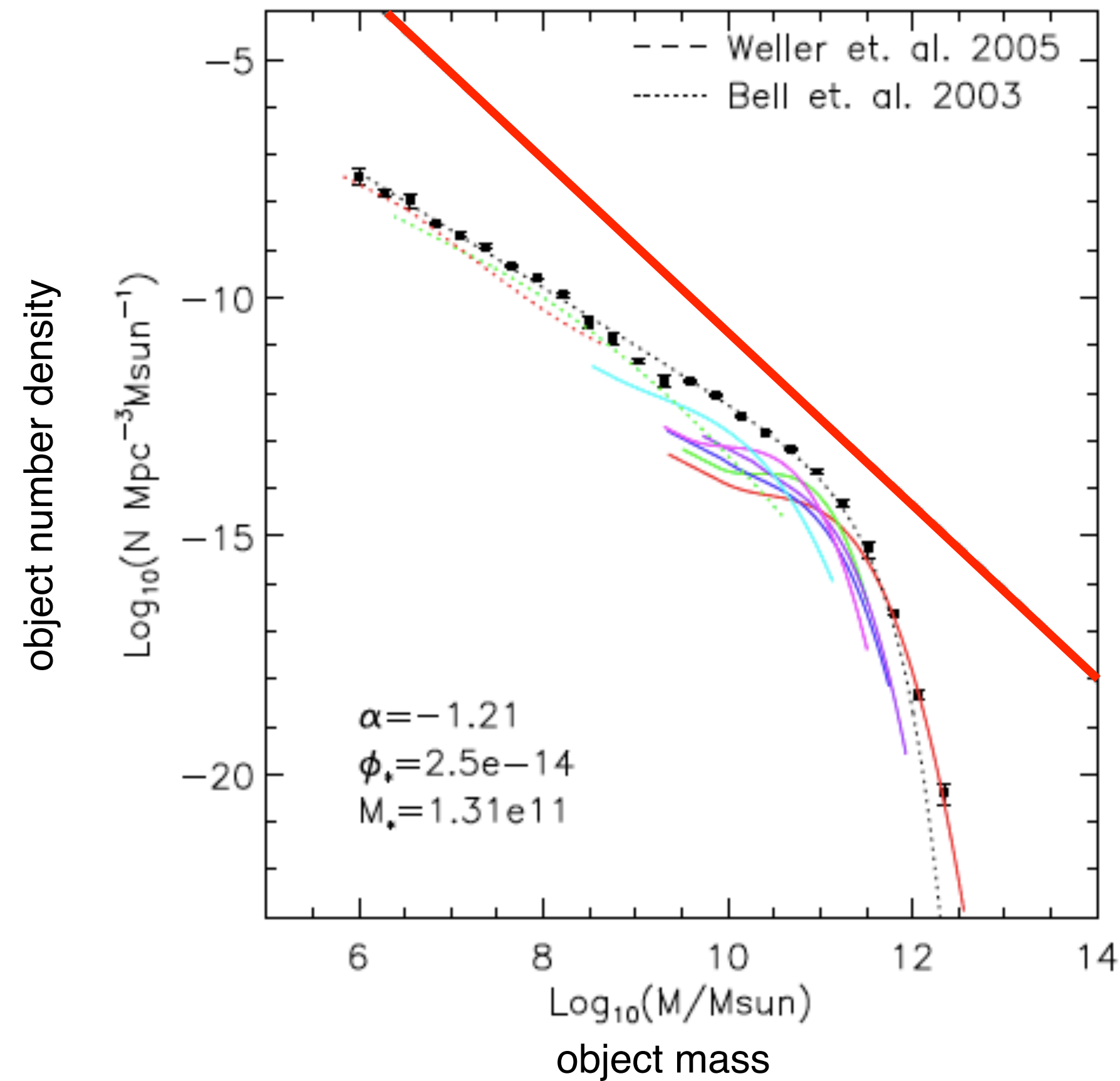


The **missing satellite problem**
or more generally
the **condensation problem** -
a mismatch between the
predicted halo mass function and
the field galaxy luminosity function

observed galaxies

Figure 4. The field galaxy baryonic mass function. The data points are for all galaxies, while the lines show spine fits by Hubble Type. The lines are as in Figure 2. The CDM mass spectrum from the numerical simulations of Weller et al. (2004) is also shown. Overlaid are parameters for a Schechter fit to the total mass function.

Baryonic Mass Function (Read & Trentham 2005)



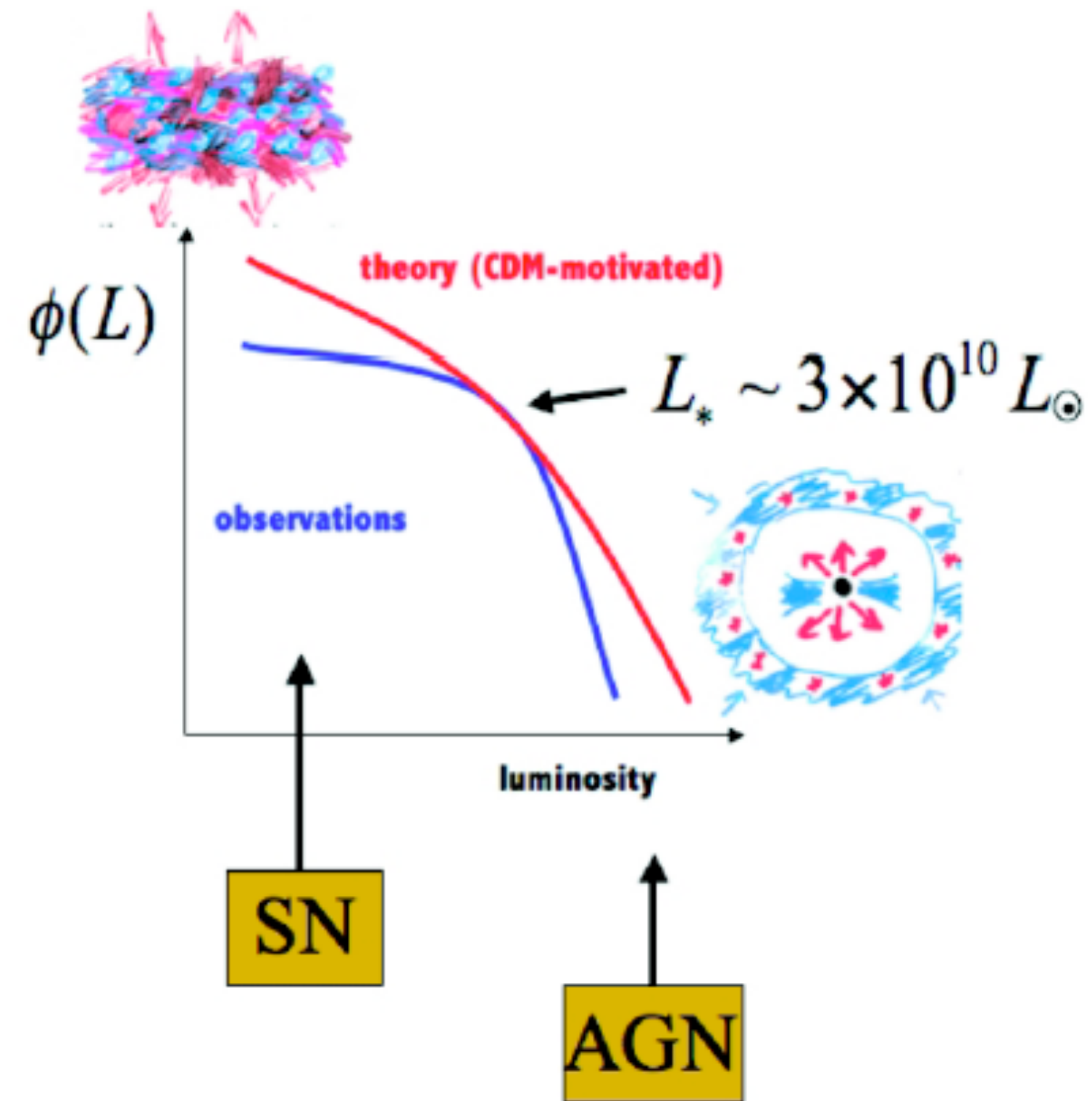
CDM halo
mass function

$$\alpha = -1.9$$

Figure 4. The field galaxy baryonic mass function. The data points are for all galaxies, while the lines show spine fits by Hubble Type. The lines are as in Figure 2. The CDM mass spectrum from the numerical simulations of Weller et al. (2004) is also shown. Overlaid are parameters for a Schechter fit to the total mass function.

Feedback

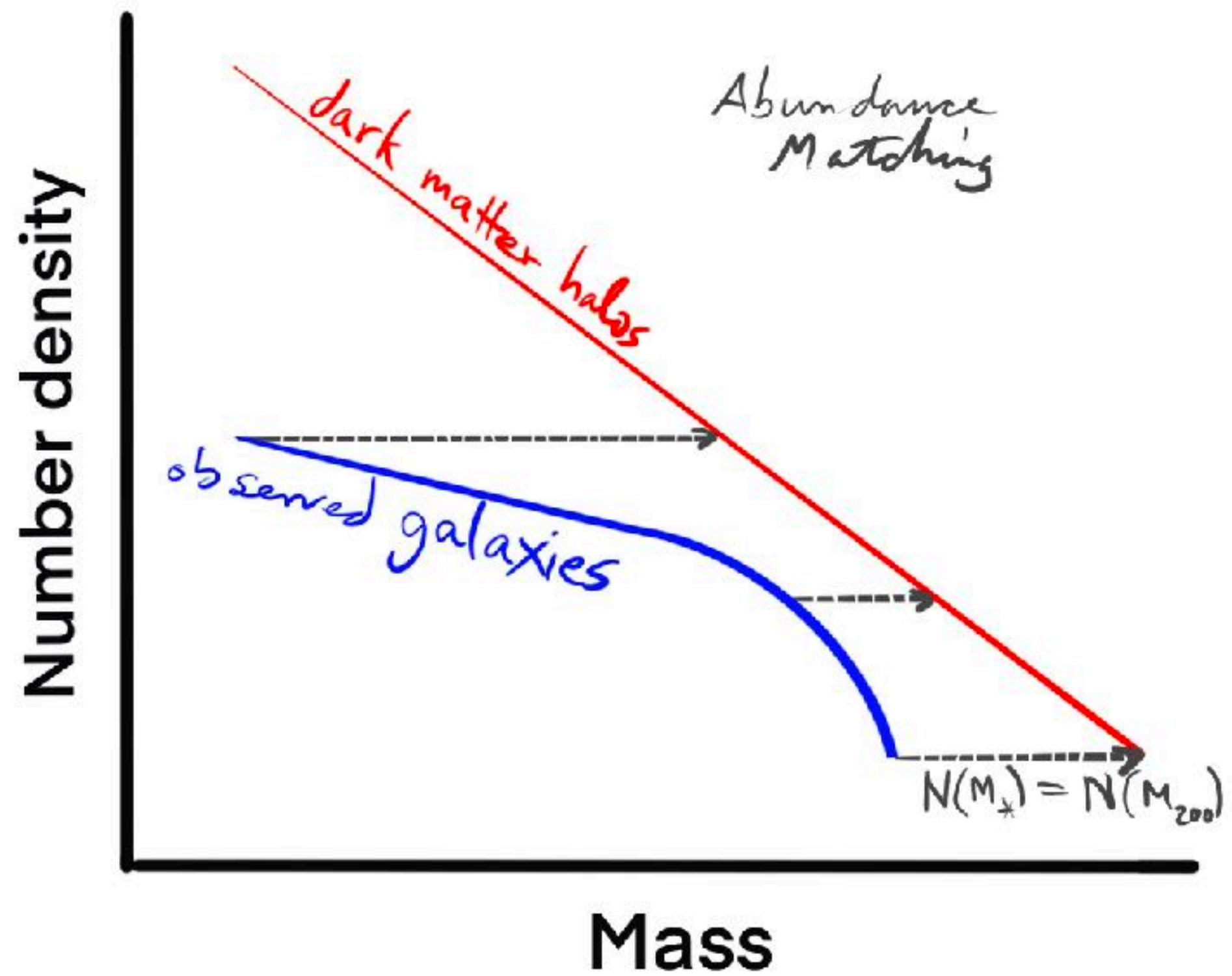
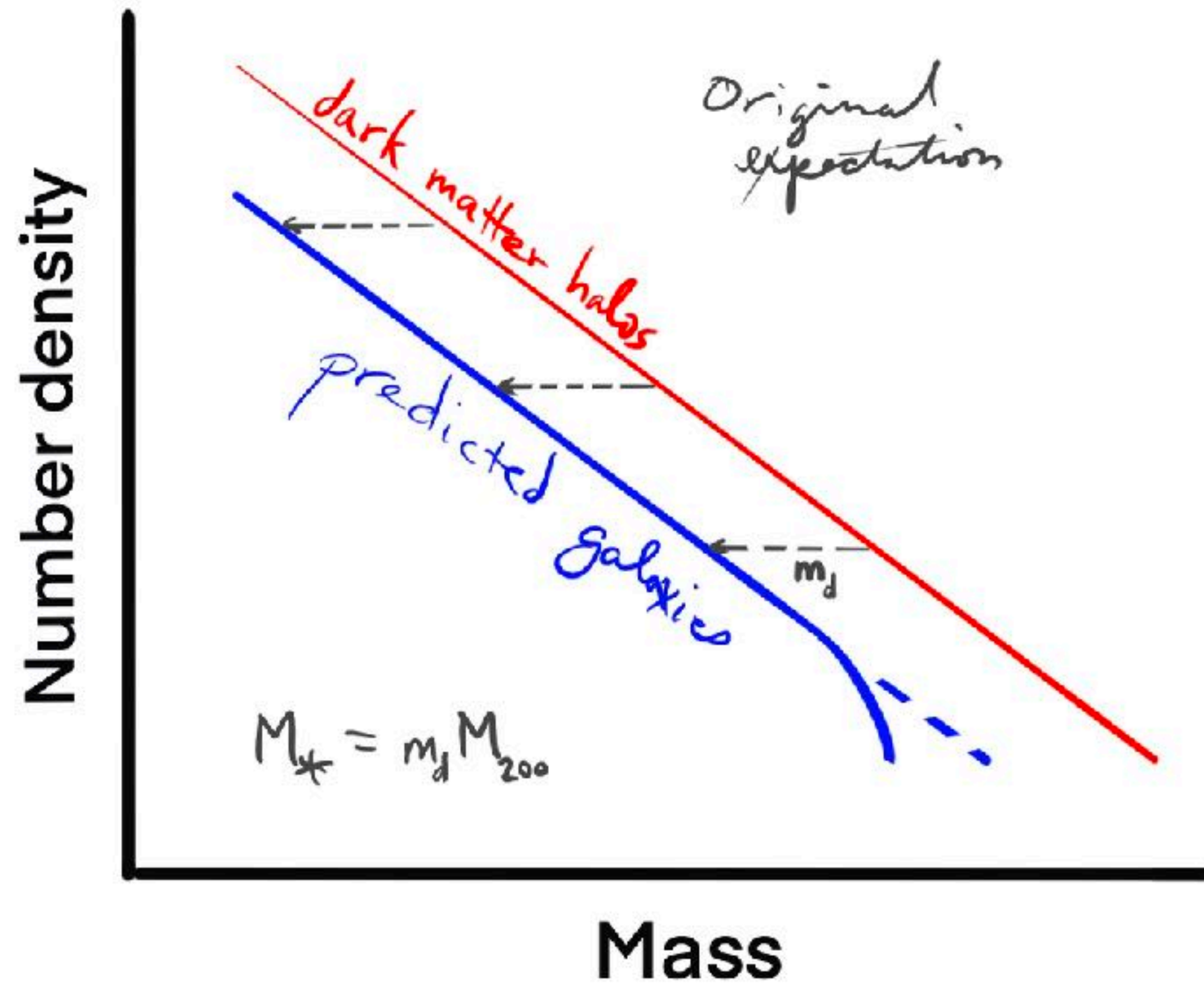
See notes for example feedback scheme (Dutton)



Basic idea: SN affect low mass halos

Energy from supernovae and other sources (e.g., stellar winds, radiation pressure) heats the surrounding gas, preventing it from cooling as expected, altering the shape of the galaxy luminosity function from the predicted halo mass function.

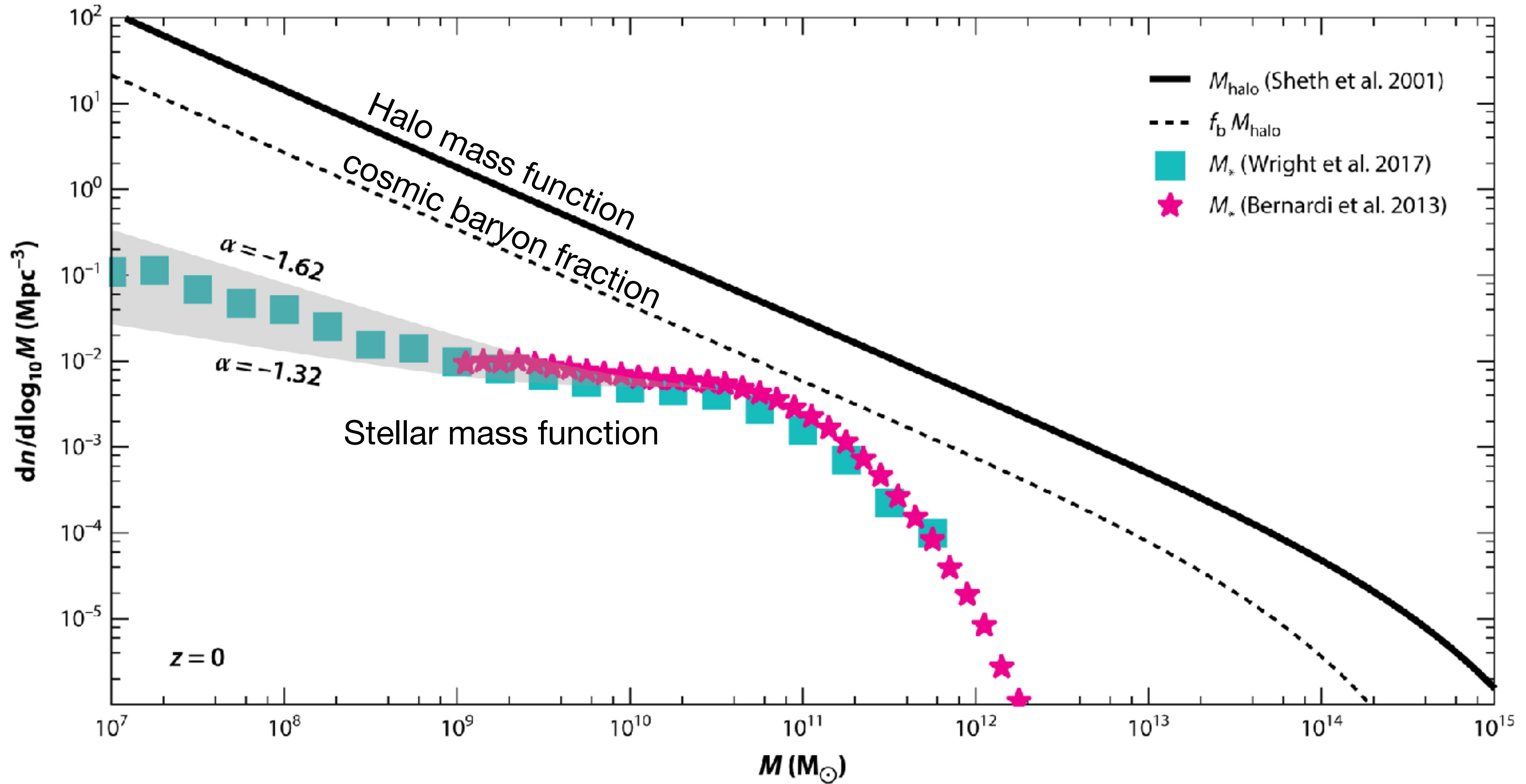
Abundance Matching



There is no predictive theory for the effects of feedback, so simply match the observed number density of galaxies to the predicted number density of dark matter halos.

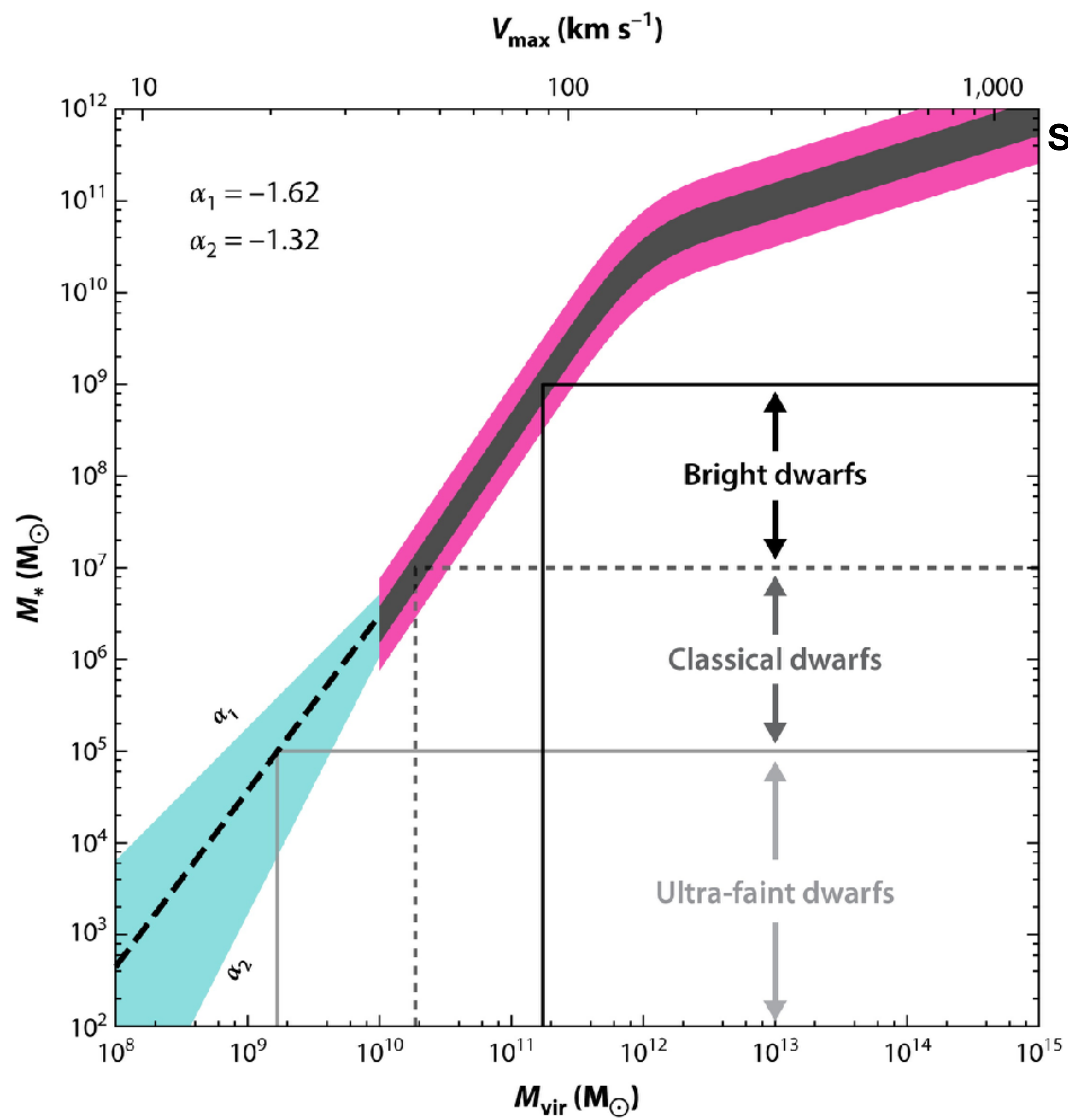
$$f_* = \frac{M_*}{M_{200}} \text{ varies with } M_*$$

Halo and stellar mass function (Bullock & Boylan-Kolchin)



$$f_* = \frac{M_*}{M_{200}} \text{ varies with } M_*$$

Abundance Matching
(Behroozi; by way of Bullock & Boylan-Kolchin)



**Stellar Mass-Halo Mass Relation
from Abundance Matching**

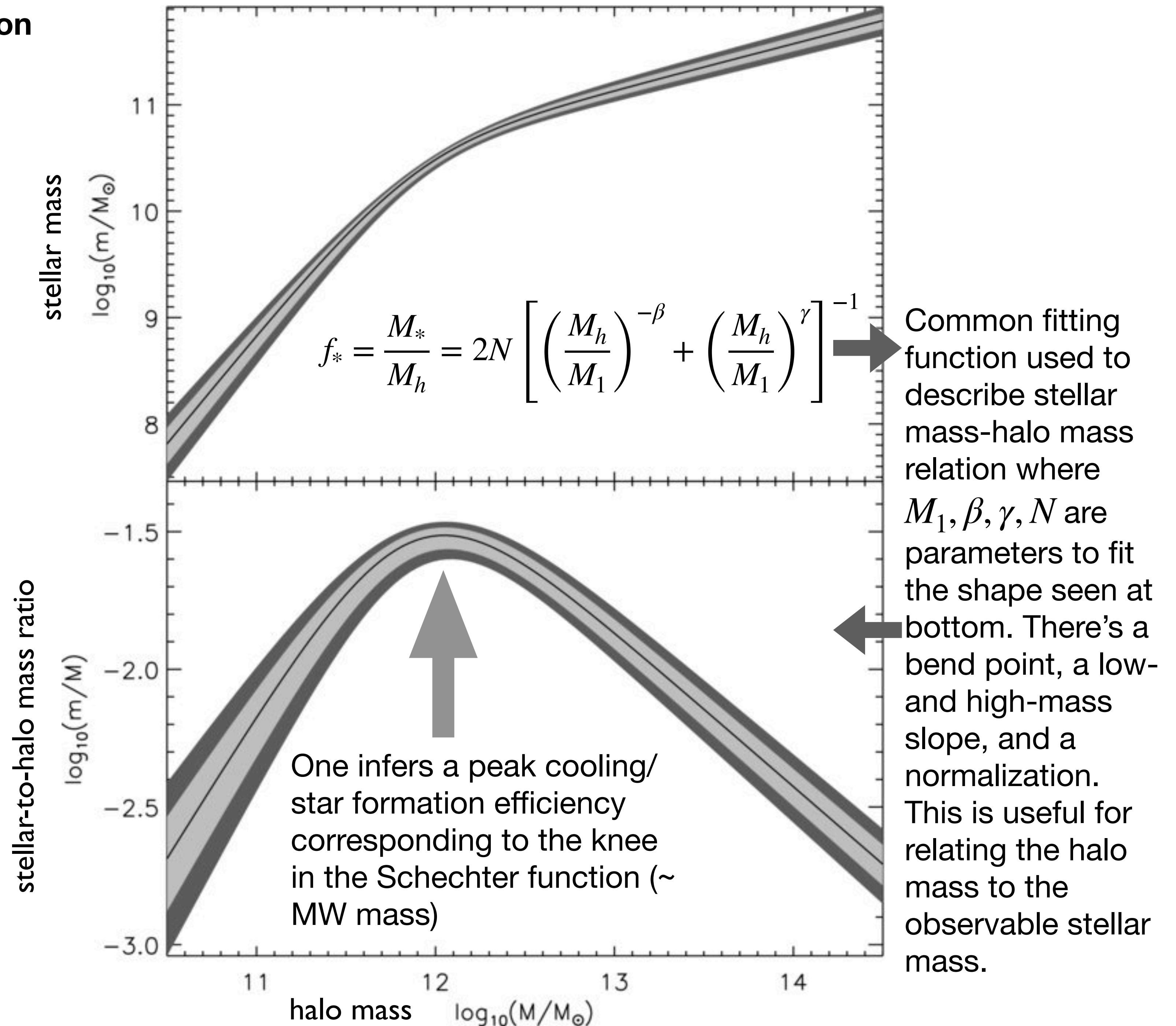
Stellar Mass-Halo Mass Relation from Abundance Matching

Behroozi et al (2013)
 Moster et al (2013)
 Kravstov et al (2019)

From
 “abundance matching”

Match the number density of simulated dark matter halos to that observed for galaxies as a fcn of mass

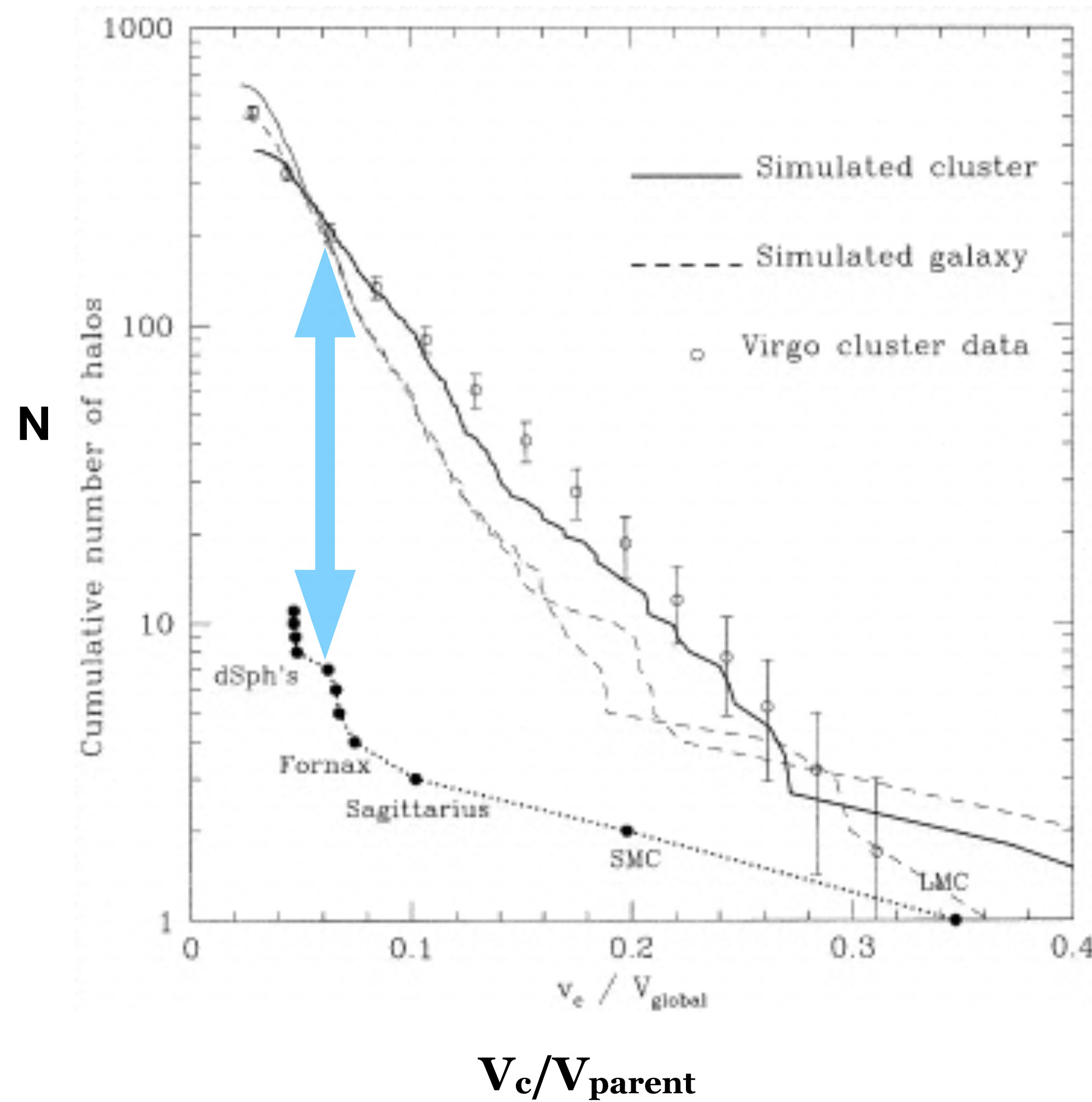
Note that a large range in stellar mass gets wedged into a narrow range in halo mass.



Missing Satellites

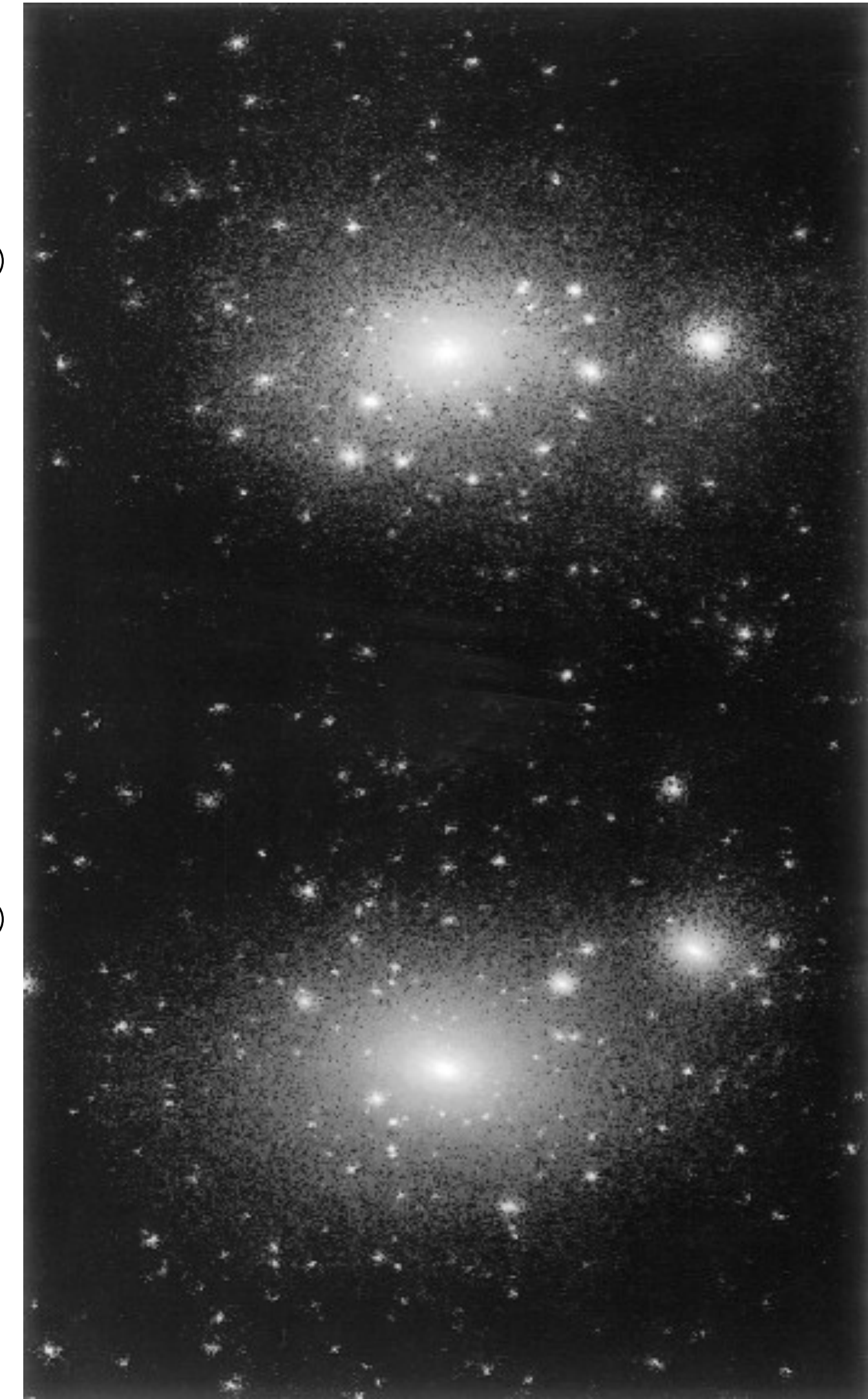
e.g., Moore et al. (1999); Klypin et al. (1999)

Same problem as with the field luminosity function:
Too few faint things. Can extend to much lower mass locally.



Cluster mass halo $5 \times 10^{14} M_{\odot}$
Galaxy mass halo $2 \times 10^{12} M_{\odot}$

CDM is scale free



Dwarf spheroidals problematic for CDM
in two distinct ways:

- there should be thousands of them
rather than dozens
(missing satellite problem)
- they have cored dark matter halos
(cusp/core problem)

*These are really just the same problems
as in the field, scaled to the Local Group*

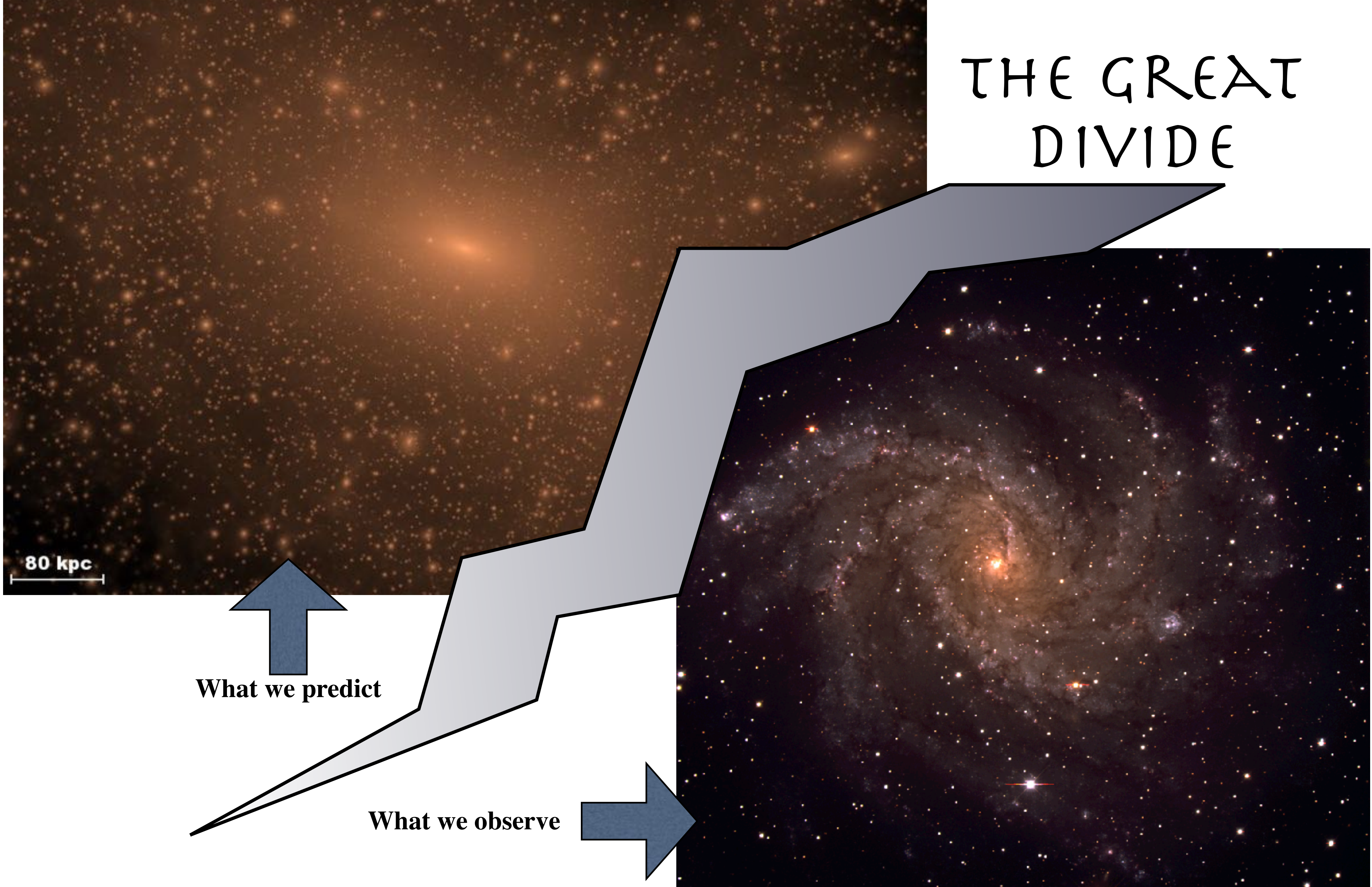
The Local Group
does not look like a simulated dark matter halo



≠



THE GREAT DIVIDE



80 kpc

What we predict

What we observe



one degree



NGC 6946

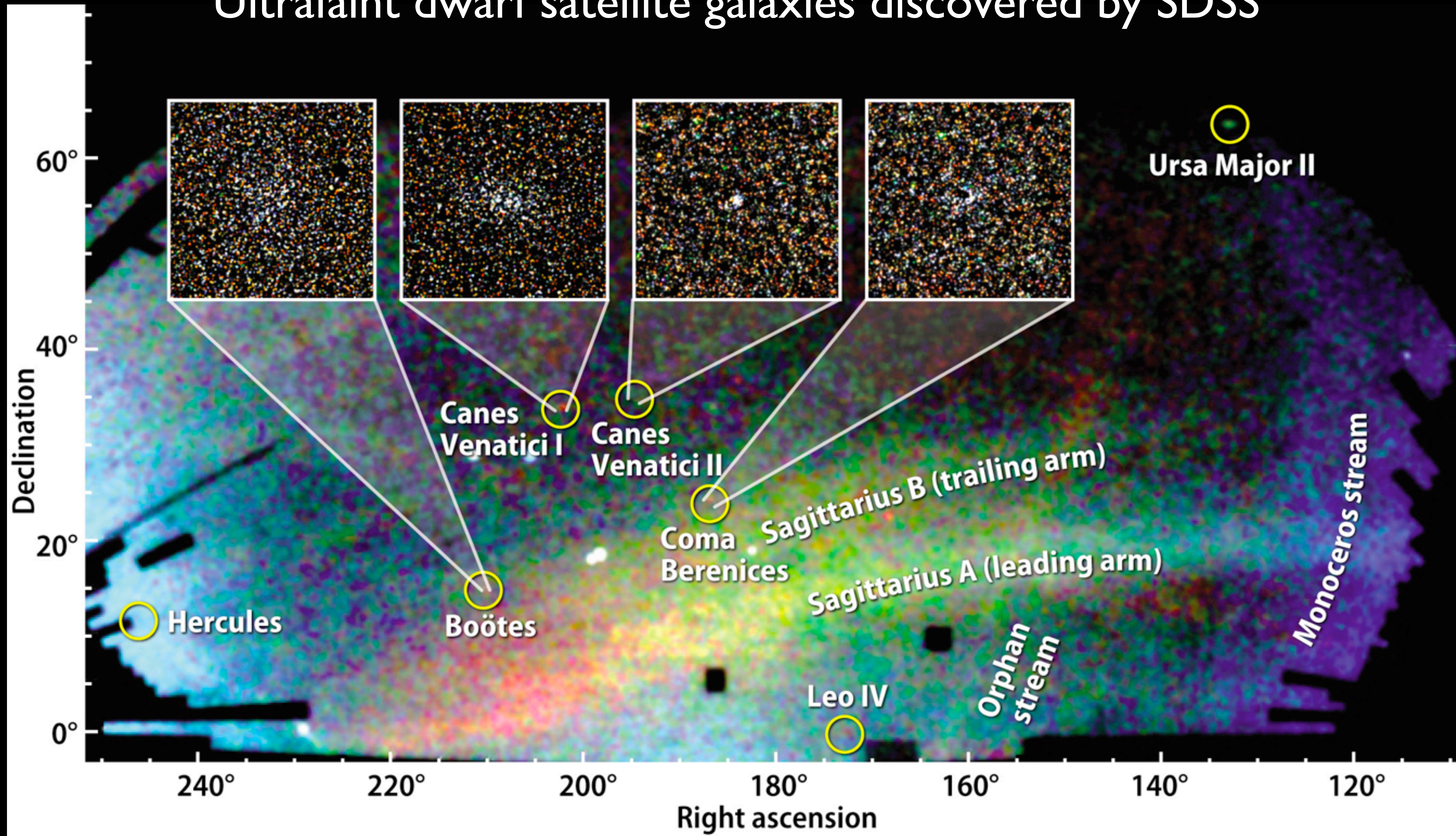


~ 70 kpc

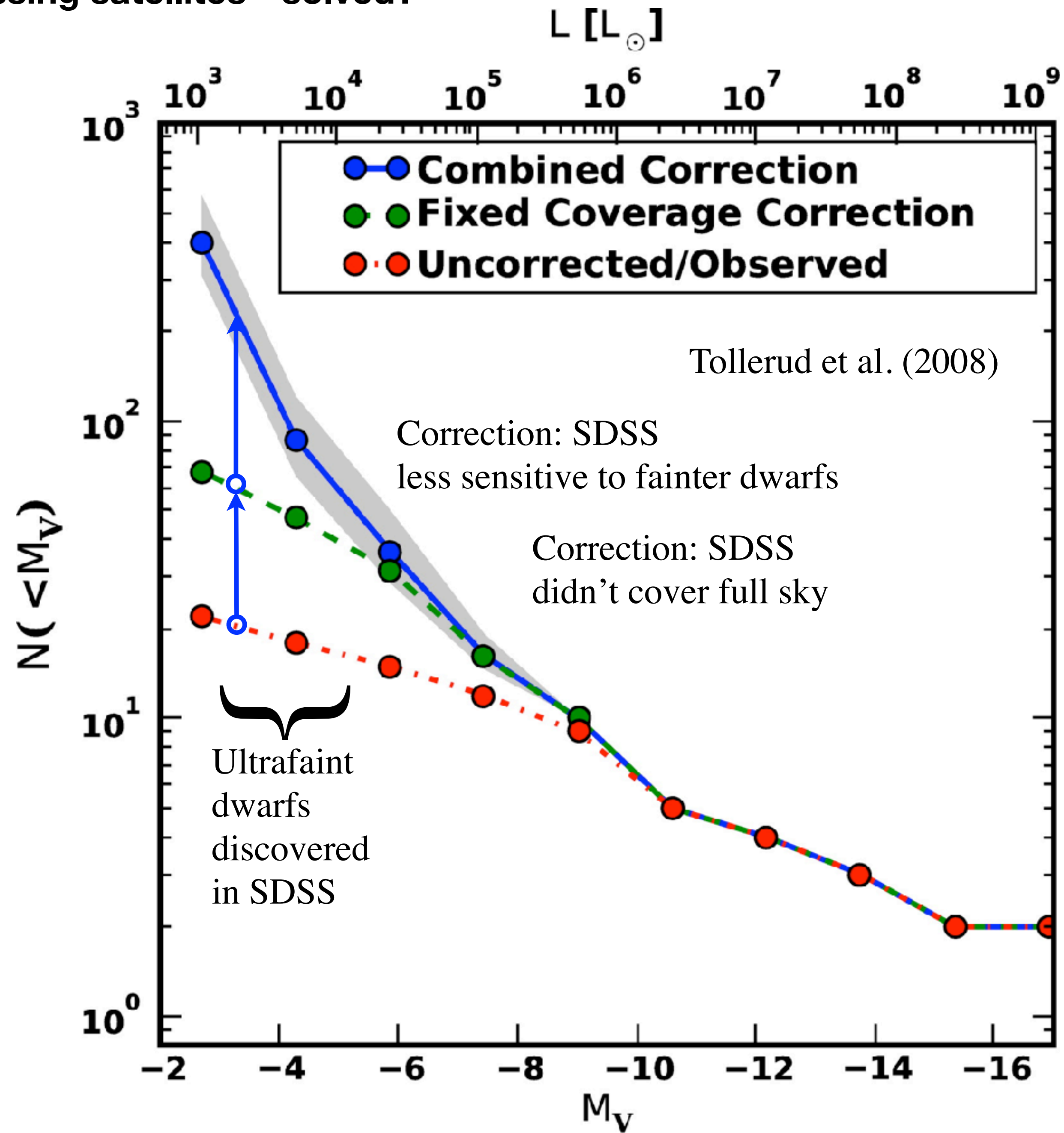
KK98-250

KK98-251

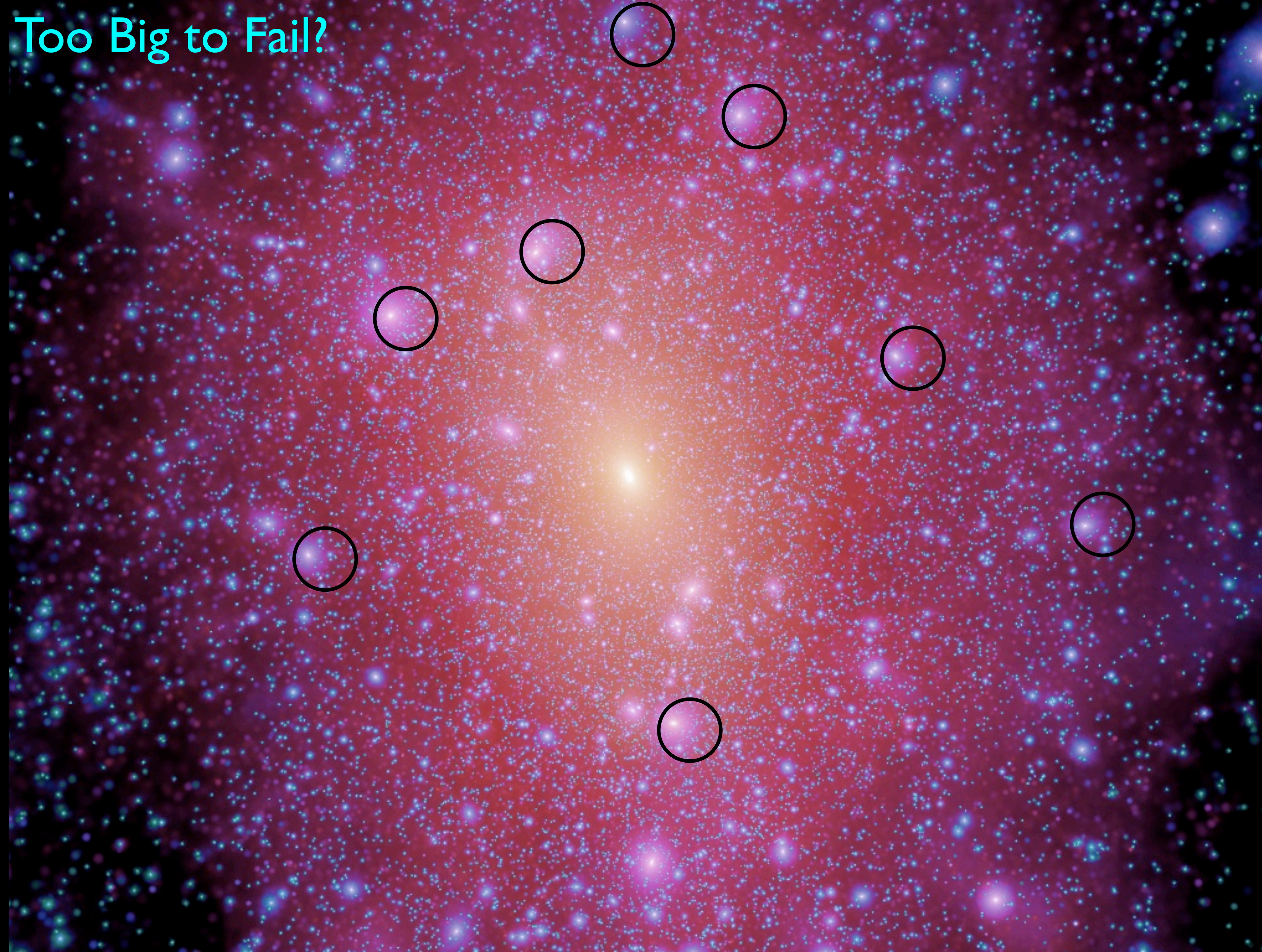
Ultrafaint dwarf satellite galaxies discovered by SDSS



Milky Way Missing satellites - solved?



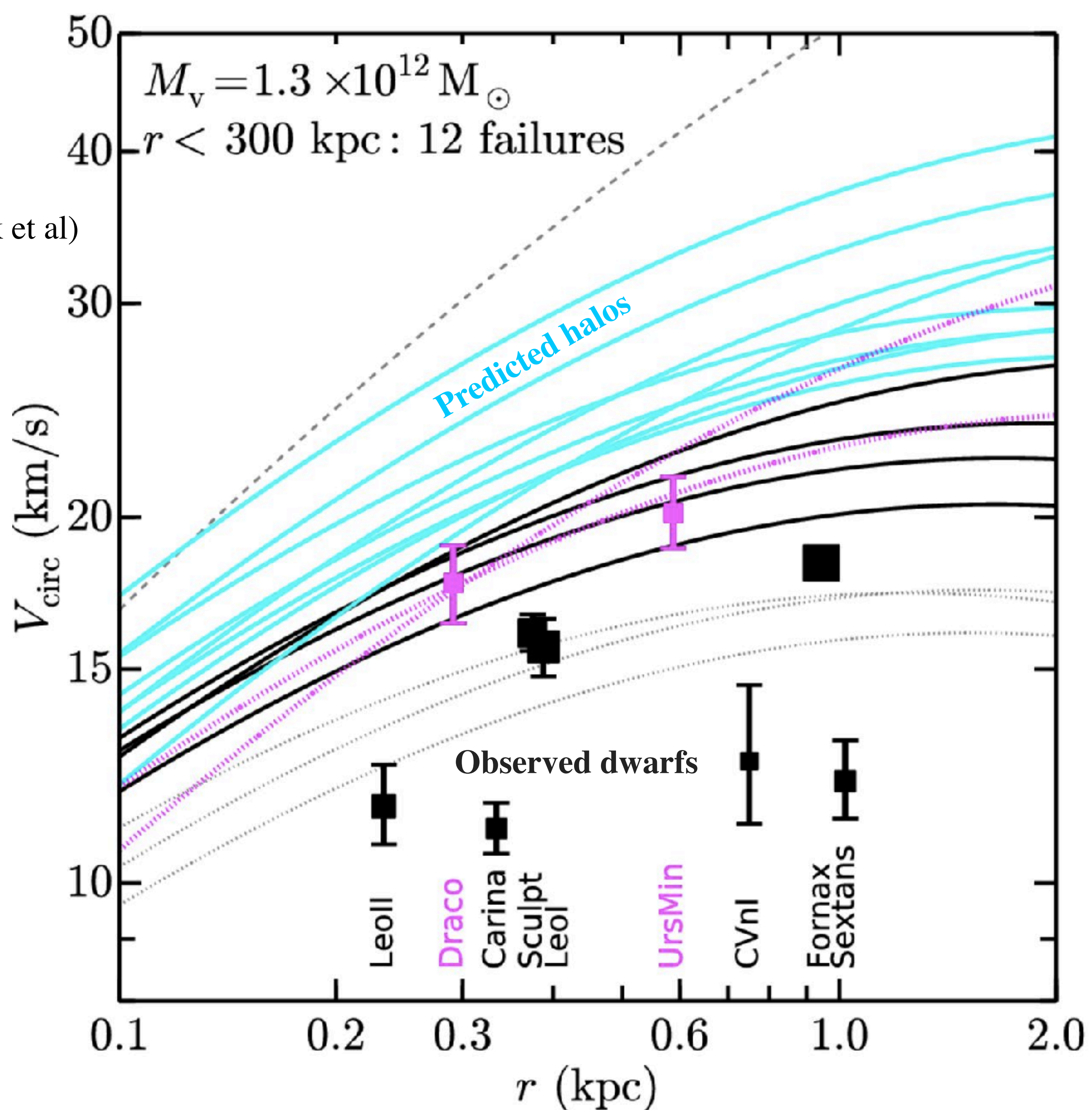
Too Big to Fail?

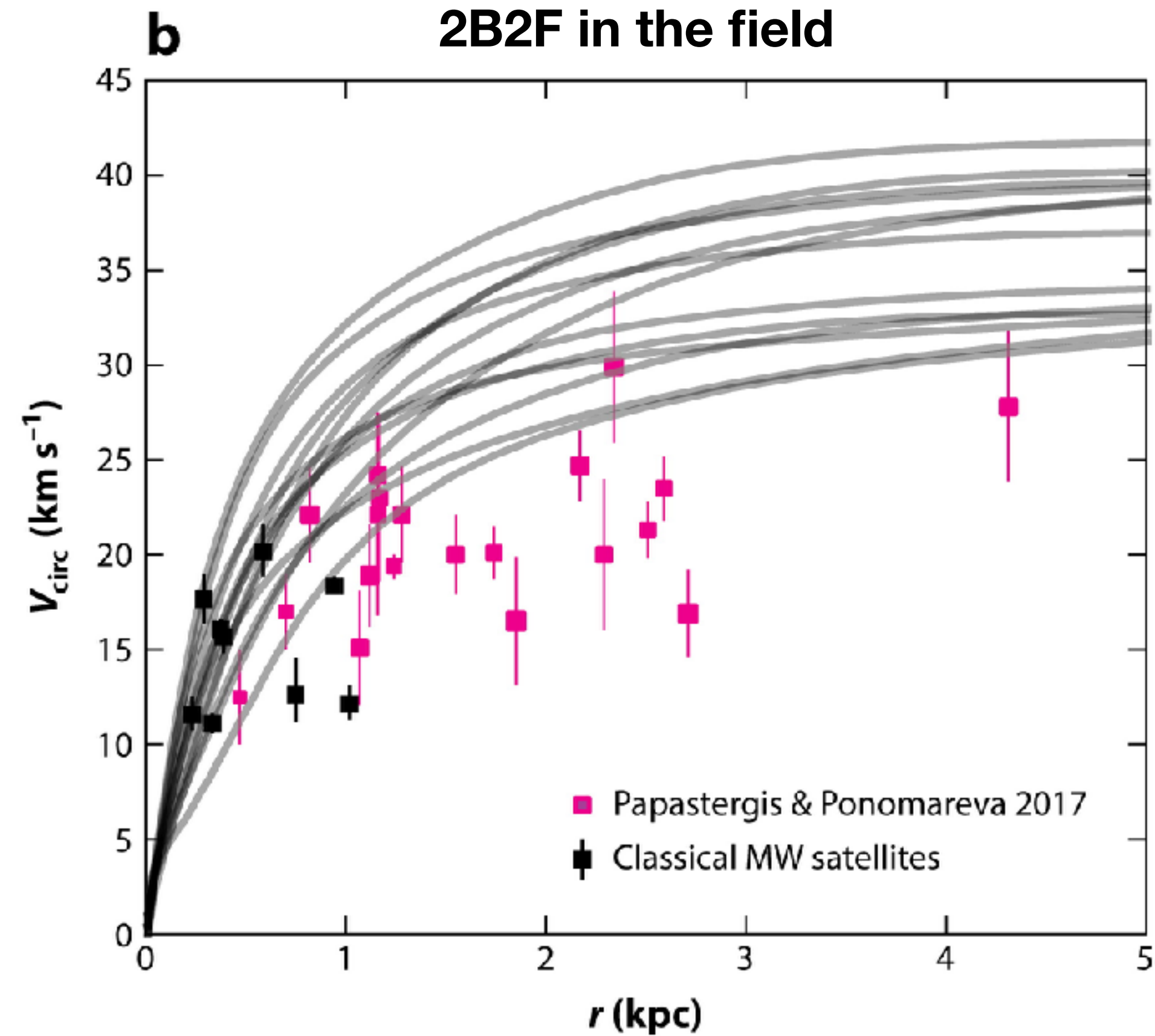
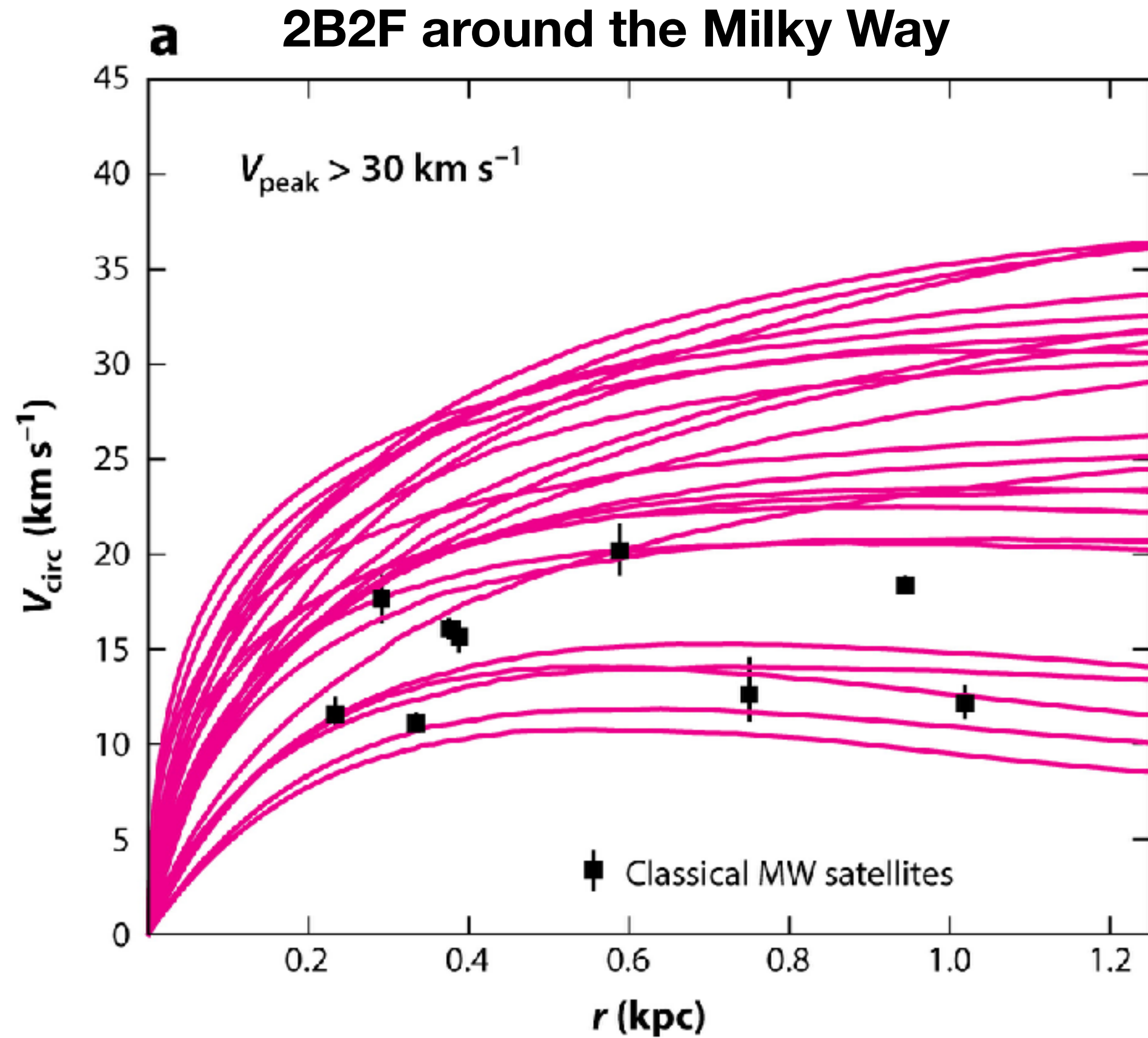


To Big To Fail

(Bovill & Ricotti;
Boylan-Kochlin & Bullock et al)

ΛCDM models predict many sub-halos that are denser & more massive than the observed dwarf satellites. If the little sub-halos managed to make dwarfs, why didn't these bigger ones?

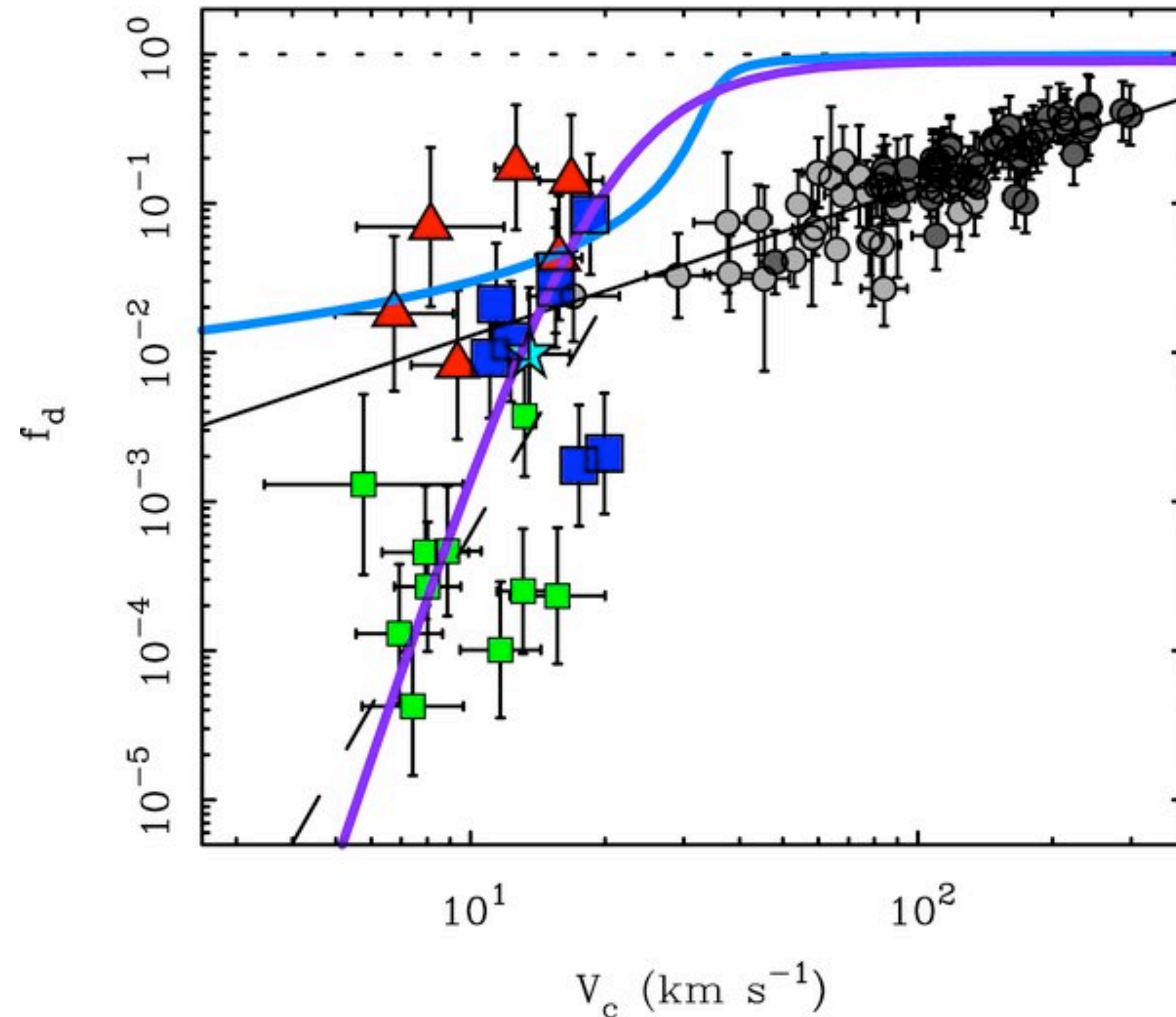




 Bullock JS, Boylan-Kolchin M. 2017.
Annu. Rev. Astron. Astrophys. 55:343–87

Too Big to Fail happens in the field, too. It can't be a process specific to satellites.
 Sort of combines the missing satellite and cusp-core problems.

Many models can be invoked to suppress galaxy formation in small dark matter halos; is harder to prevent in mid-size halos.

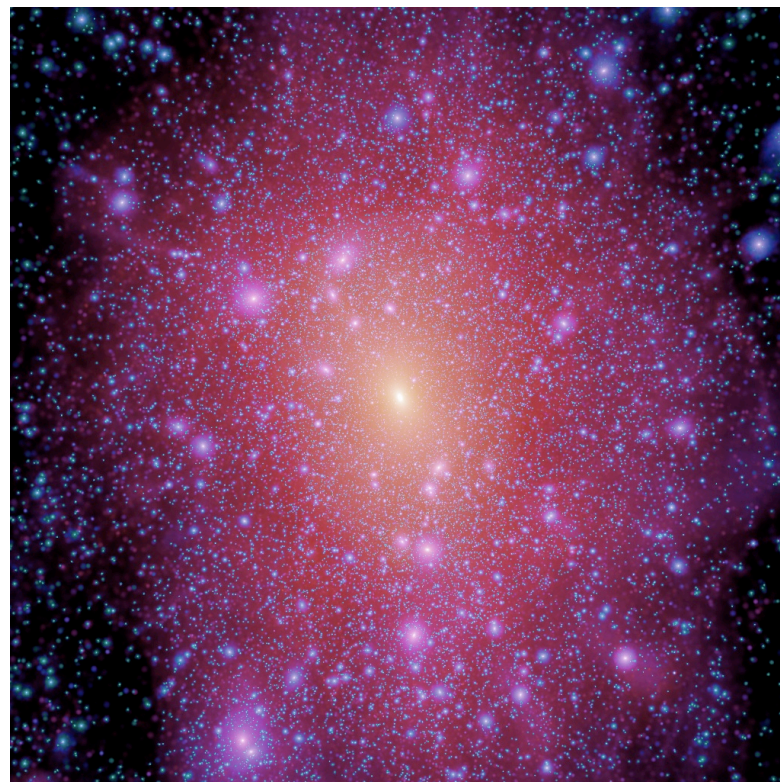


e.g., Reionization models illustrated here are good for explaining the smallest galaxies, but not ~ 40 km/s halos, which are too big to fail.

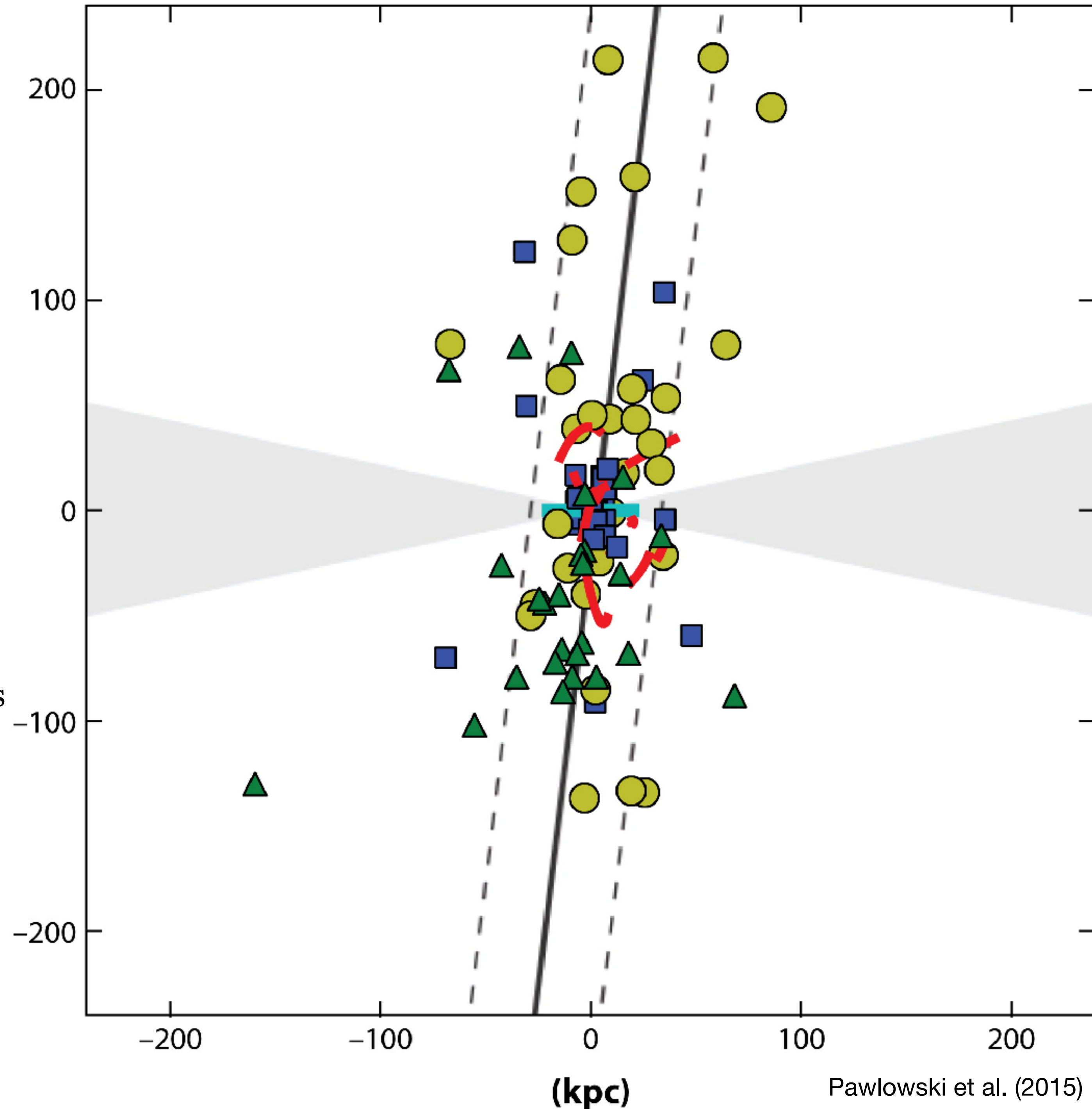
Planes of satellites

Dwarf satellite galaxies of the Milky Way, Andromeda, and Cen A are observed to be orbiting on quasi-circular orbits confined to narrow planes.

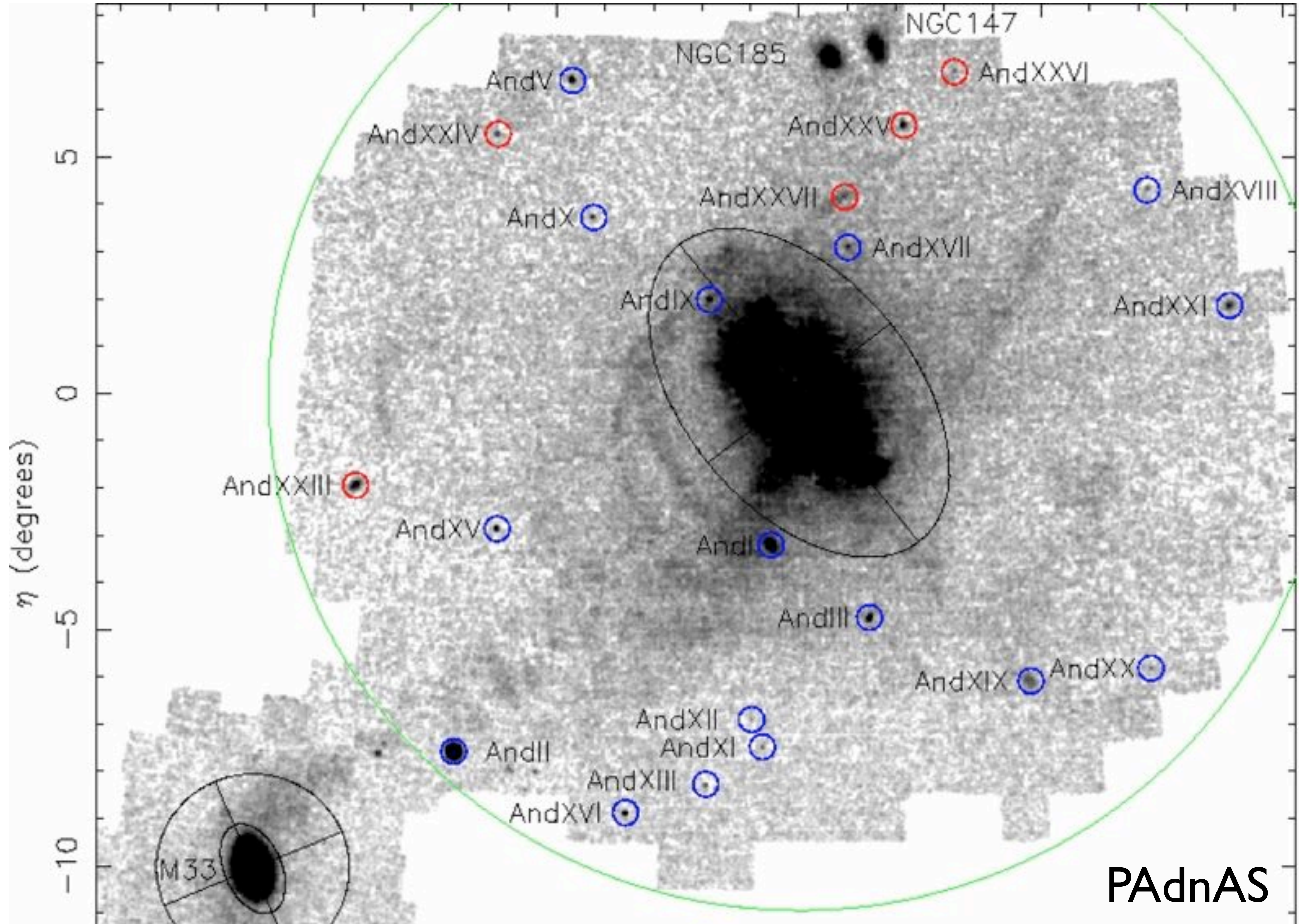
In DM simulations, the sub-halos thought to host dwarf satellites have highly radial orbits that are randomly oriented.



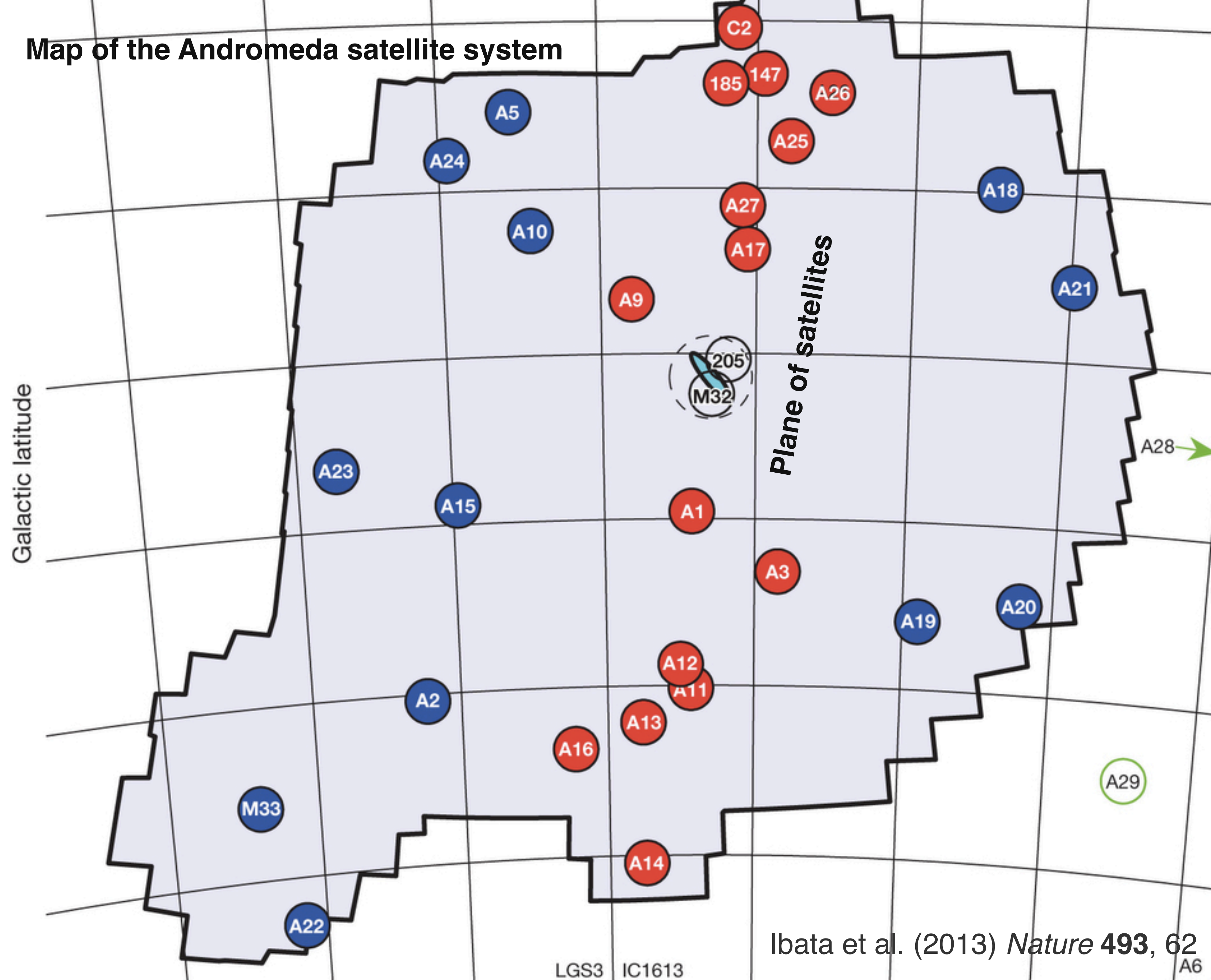
(kpc)



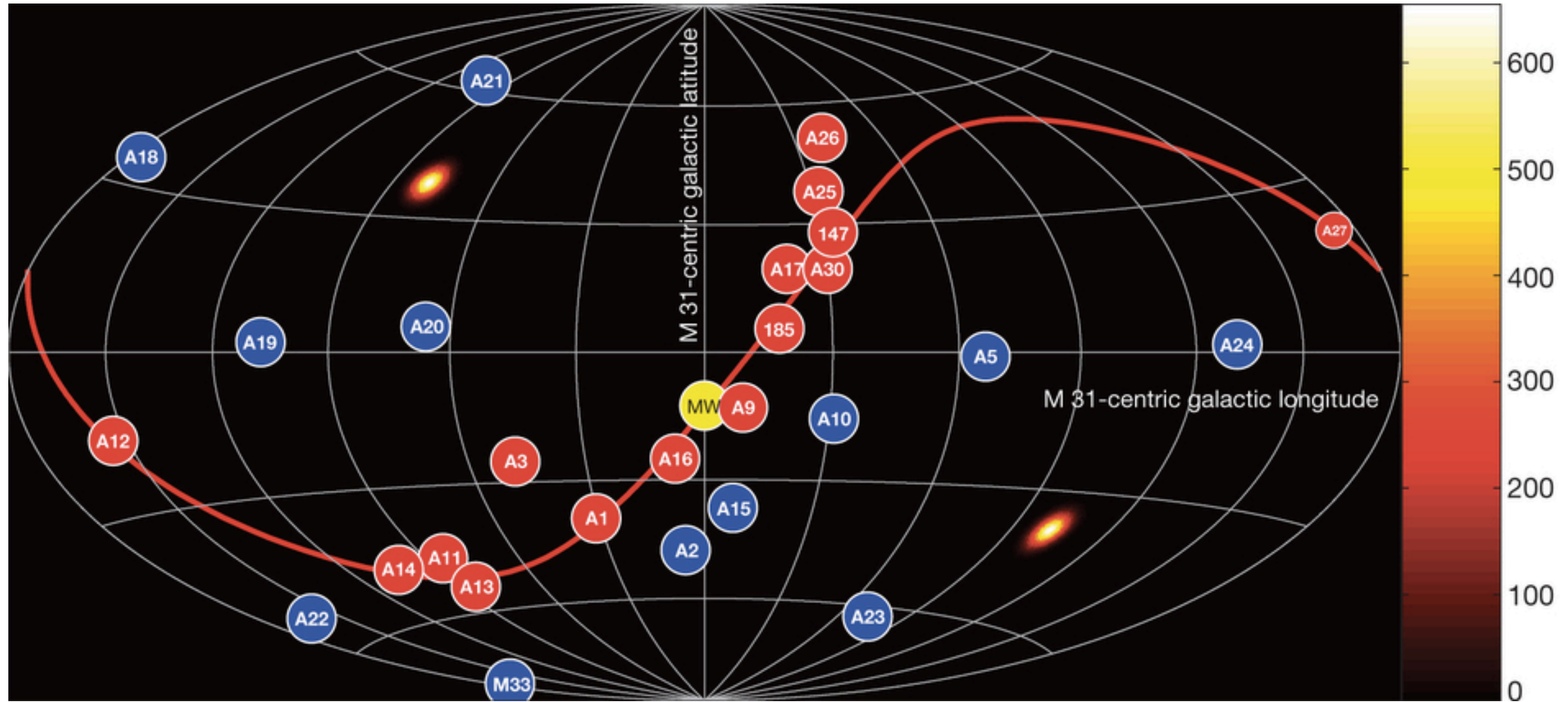
The dwarf satellites of Andromeda



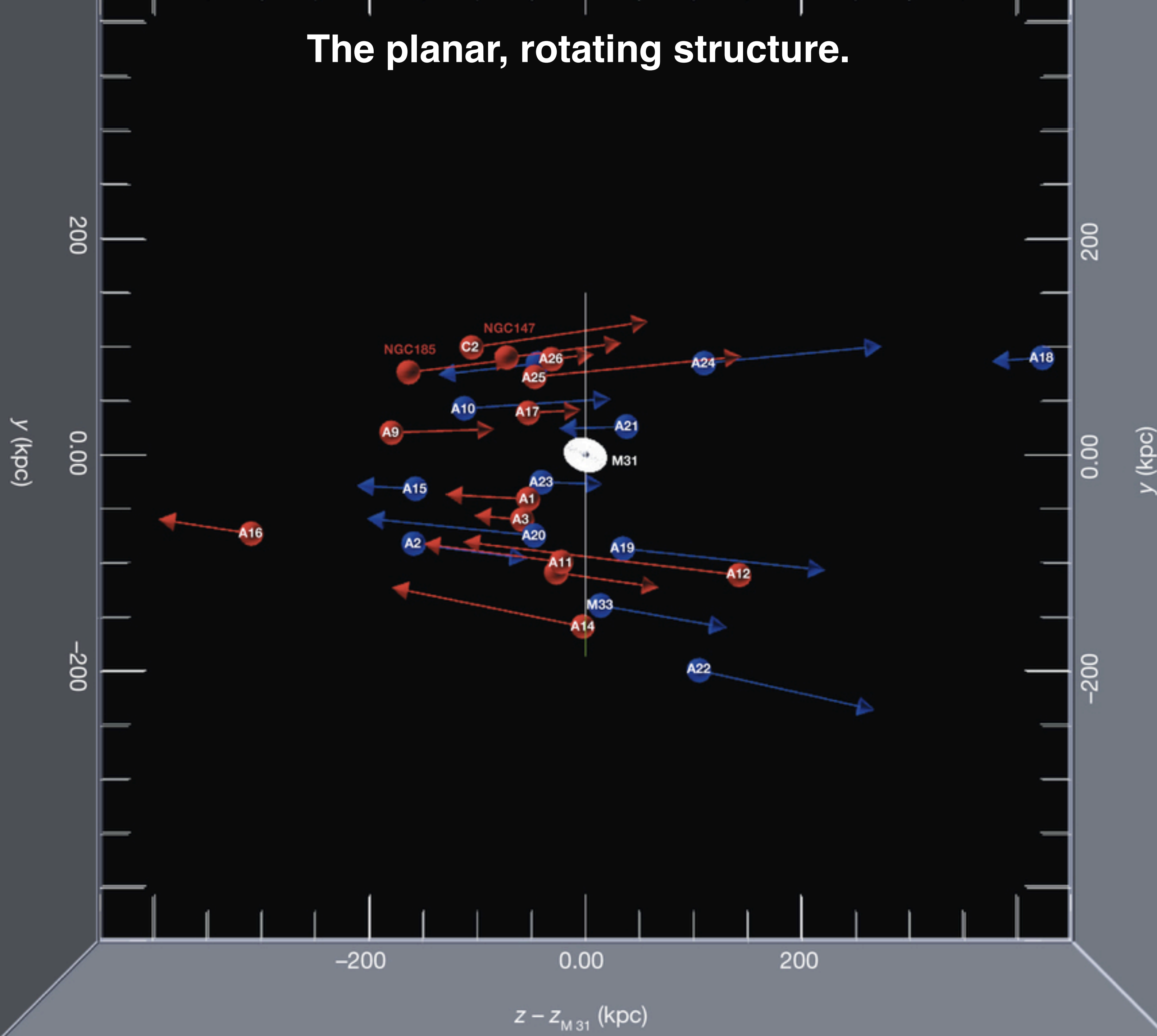
Map of the Andromeda satellite system

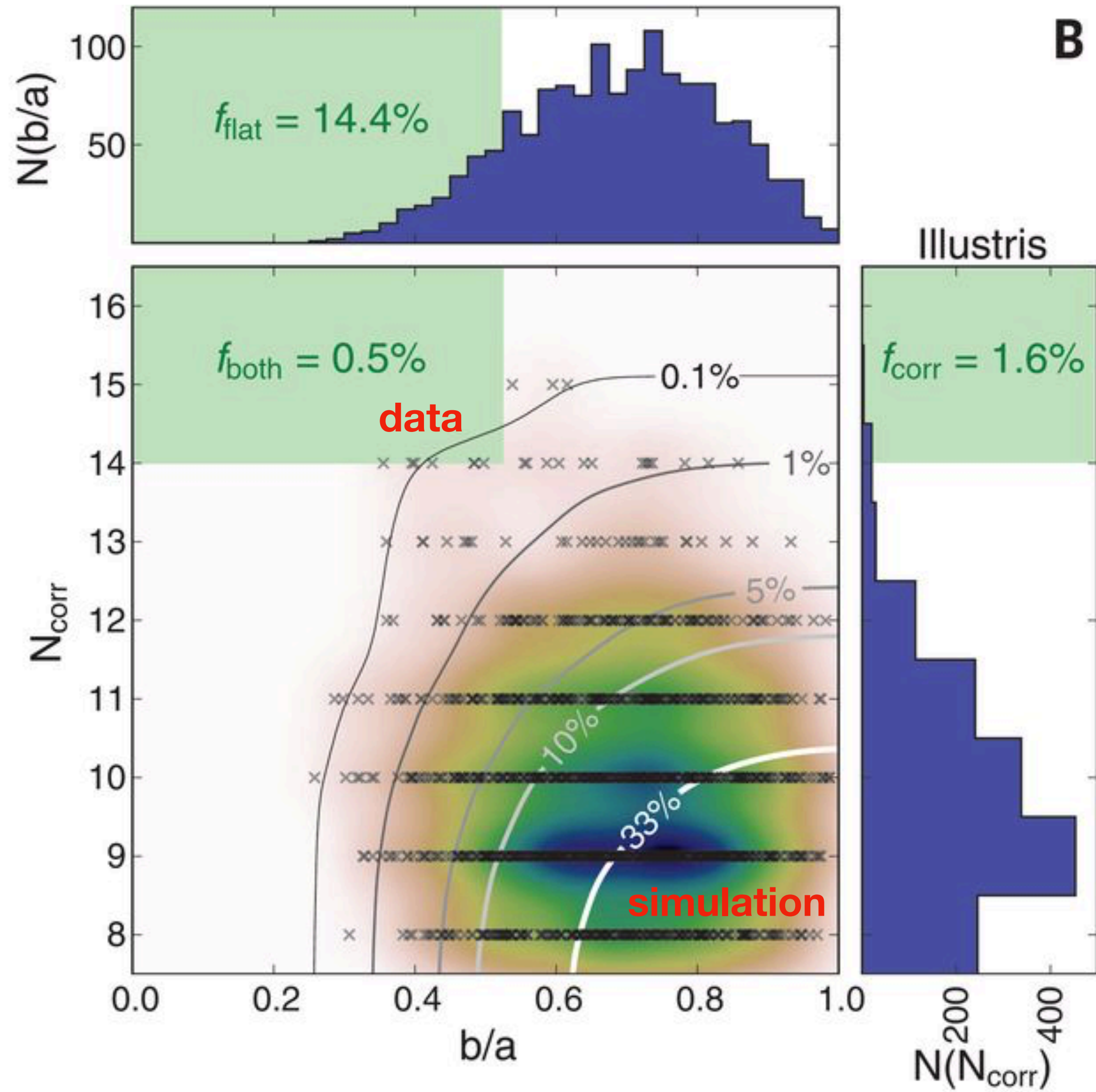
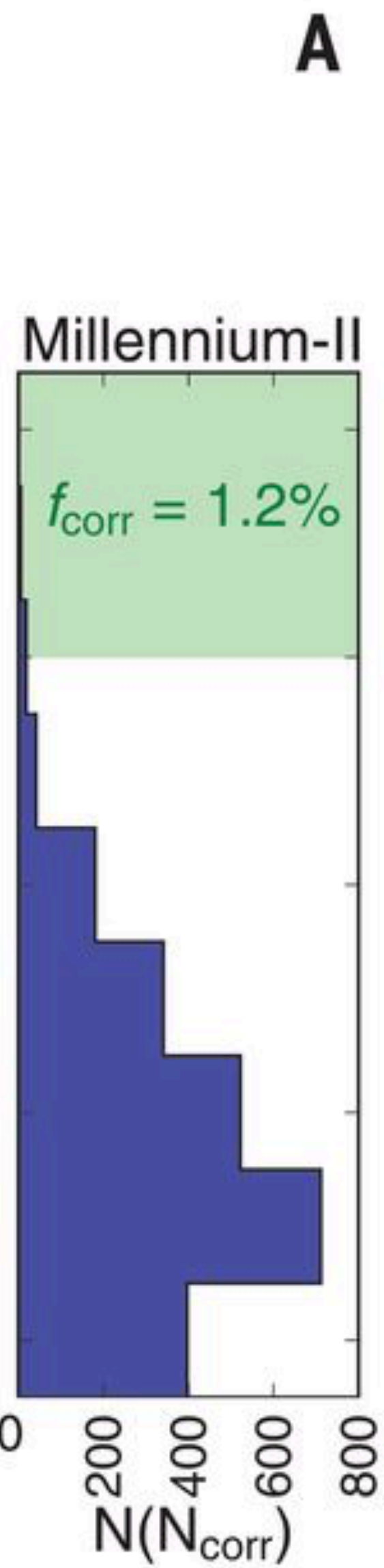


Satellite galaxy positions as viewed from Andromeda



The planar, rotating structure.





The chance of the satellite plane of Cen A being both as flattened and as kinematically correlated as observed is $< 1\%$ in simulations

Dwarf satellite galaxies are problematic for CDM in several ways:

- Missing Satellites
 - should be thousands rather than dozens
- Cusp/core problem
 - dark matter halos lack central cusps
- Too Big To Fail
 - dearth of intermediate mass satellites
- Satellite Planes
 - satellites tend to reside in narrow, co-orbiting planes